

## Chapter 3

### Site Characterization and Technology Screening

#### 3-1. Introduction

This chapter describes SVE/BV technologies and their applicability to different types of contaminants and sites. Guidance on screening level evaluation of SVE/BV is provided, along with several examples of screening evaluations.

#### 3-2. SVE/BV Technology Options

To familiarize the reader with the range of technology variations available, the following subsections introduce various SVE/BV remedial options.

*a. Soil vapor extraction.* SVE can be a cost-effective way to remove VOCs from unsaturated soils. Other names for SVE include “soil venting,” “soil vacuum extraction,” “vacuum extraction,” “subsurface venting,” “soil gas vapor extraction,” “in situ venting,” “enhanced volatilization,” and “vapor extraction.”

(1) Airflow is induced in the subsurface by applying a pressure gradient through vertical or horizontal wells or horizontal trenches. In SVE, this is usually accomplished by withdrawal, rather than injection, of air. The SVE gas flow increases rates of contaminant mass transfer to air in the unsaturated zone by evaporation of NAPL, volatilization of contaminants dissolved in pore water, and desorption of contaminants from soil particle surfaces. SVE is dependent on contaminant properties, such as volatility, and soil properties, such as air permeability and stratigraphy.

(2) SVE is often used in conjunction with other remediation technologies that treat the resulting contaminated air and water streams. Sometimes ancillary technologies such as soil heating and subsurface fracturing are also used in an effort to further enhance transport rates. SVE is usually required in conjunction with air sparging systems to extract the generated contaminated air from the subsurface.

(3) SVE systems vary, but a typical SVE system schematic is provided in Figure 3-1. It consists of one or more extraction wells, an air/water separator, and a blower or vacuum pump. It may also include one or more air inlet or injection wells, an impermeable cap at the ground surface, and treatment systems for the air and/or water streams. Air may need to be filtered prior to injection. Contaminated condensate (water condensed from the extracted air stream) may be treated offsite.

(4) SVE treatment rates are highly site-specific, varying greatly as a function of such factors as air permeability, contaminant concentrations, cleanup standards, and offgas treatment system characteristics. The number of pore volume exchanges necessary to complete a cleanup is likewise highly variable, but a typical number might be 5,000 pore volumes (Beckett and Huntley 1994). To complete remediation in 1 to 2 years would necessitate about 10 pore volume exchanges per day.

(5) In the United States, SVE has been used at leaking UST sites and for methane removal at landfills since the 1970s (Emcon 1980; U.S. District Court 1994). Thornton and Wootan (1982) discussed the

concept of vertical vapor extraction to remove gasoline. Texas Research Institute (1984) presented various venting geometries and described a venting test in a pilot-sized soil tank. Marley and Hoag (1984) conducted laboratory SVE tests on packed gasoline-contaminated soil columns and measured and modeled the concentrations of gasoline constituents in the extracted gas. Hoag and Cliff (1985) reported on SVE of gasoline-contaminated soil at a service station; 1,330 liters of gasoline were removed in 100 days, achieving cleanup levels of 3 ppm or less in soil vapor and nondetectable concentrations in soil. Other early field applications for hydrocarbon removal are described in Batchelder, Panzeri, and Phillips (1986), Crow, Anderson, and Minugh (1986), and USEPA (1989a). Some of the early applications of SVE to solvents and other hazardous wastes are summarized in USEPA (1989a). USEPA documents six Superfund Remedial Actions at which SVE has been completed, including a 53,500 m<sup>3</sup> portion of the Rocky Mountain Arsenal contaminated with tetrachloroethylene (PCE) and 1,480,000 m<sup>3</sup> at Fairchild Semiconductor contaminated with chlorinated hydrocarbons (USEPA 1993b). SVE is widely used in Europe (Hiller 1991, Dieter Baumgarten, personal communication, 1999).

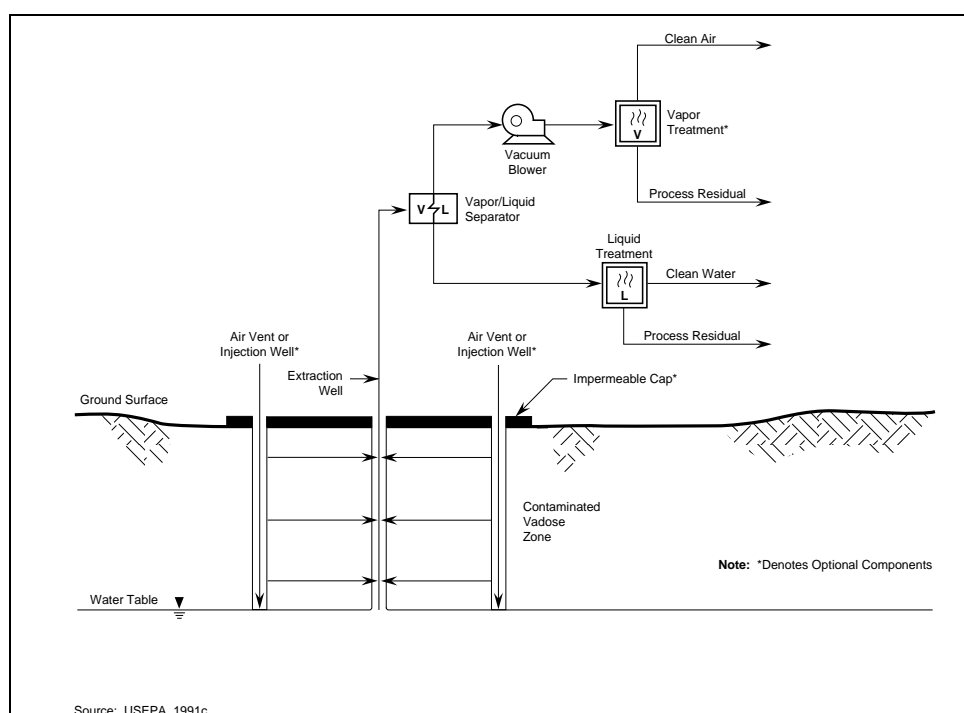


Figure 3-1. Generic soil vapor extraction system.

*b. Bioventing.* BV is the process of advecting gases through subsurface soils to stimulate in situ biological activity and enhance bioremediation of contaminants. It generally involves supplying oxygen in situ to oxygen-deprived soil microbes by forcing air through unsaturated contaminated soil at low flow rates (Hoepfel, Hinchee, and Arthur 1990). Compounds that are readily aerobically biodegradable in the vadose zone include linear (and some branched) alkanes; mono-aromatic compounds such as benzene, toluene, ethylbenzene, and xylenes (BTEX); and, to a somewhat lesser extent, two-ring aromatic compounds such as naphthalene.

(1) Co-substrates such as methane and nutrients such as ammonia can also be introduced into the subsurface in the gaseous phase. Airflow can be induced by air injection or withdrawal. Air injection is often preferred because it may eliminate the need for offgas treatment (Figure 3-2); however, air

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withdrawal and treatment may be preferred if there is a concern that vapors could migrate to nearby basements or other structures.

(2) BV is similar to SVE, but its primary goal is different. They both usually involve volatilization and biodegradation, but whereas the goal of SVE is to volatilize and remove the air phase contaminants from the subsurface as quickly as possible, BV attempts to maximize the rate of biodegradation. BV utilizes low airflow rates to provide only enough oxygen to sustain optimal microbial activity (e.g., vapor-phase oxygen concentrations at or above 5 percent). Hinchee, Arthur, and Miller (1991a) state that approximately one pore volume exchange of air per day is sufficient to support biodegradation, while more recent field

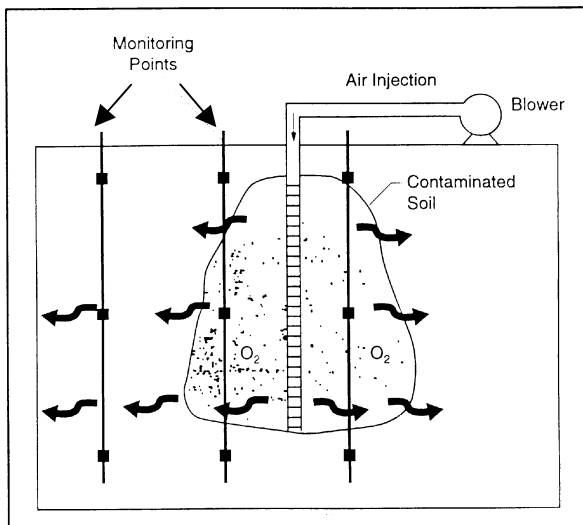


Figure 3-2. Typical bioventing system (AFCEE, 1994).

experience with full-scale BV systems suggests that 0.25 to 0.5 pore volumes may be optimal in terms of maximizing biodegradation while minimizing volatilization. This lower exchange rate minimizes the mass of volatilized contaminants in offgas that may need to be treated aboveground, and increases the residence time of volatilized contaminants in the subsurface for maximum destruction by biodegradation. Whereas SVE is limited to treating volatile contaminants, BV can also be used to remediate contaminants of low volatility such as fuel oil and diesel constituents (Miller et al. 1993). The remediation time frame for such low-volatility and low-solubility contaminants may be long, however.

(3) Studies in the early 1980s by Texas Research Institute (1980, 1984) first indicated that SVE stimulated biodegradation, which may have accounted for as much as 38 percent of the removal of gasoline from the vented soils. During the same period, researchers conducting experiments for Shell Research in the Netherlands made the first field observations of venting-induced biodegradation (van Eyk and Vreeken, 1988). Wilson and Ward (1986) proposed using air to enhance biodegradation in the unsaturated zone, and Bennedsen, Scott, and Hartley (1987) concluded that SVE is an effective way to provide oxygen to the subsurface for enhanced biodegradation. Natural biodegradation occurs in the subsurface, but at rates dependent on oxygen diffusion (Ostendorf and Kampbell 1989, 1991). In the late 1980s and early 1990s, the U.S. Air Force (USAF) carried out field-scale SVE and bioventing research at several bases, including Hill AFB in Utah and Tyndall AFB in Florida (DePaoli et al., 1991; Miller et al., 1991). This work was expanded to include bioventing testing at over 125 sites, in an effort the Air Force Center for Environmental Excellence (AFCEE) termed their Bioventing Initiative (Miller et al., 1993; AFCEE, 1996). The USAF now considers bioventing to be a presumptive remedy for sites contaminated with jet fuel. Recommendations stemming from the Bioventing Initiative are provided in Principles and Practices of Bioventing (Leeson and Hinchee, 1995).

*c. Passive Venting.* Although in most cases mechanical blowers are used to induce the air movement for either SVE or bioventing, natural barometric pressure changes can be used to induce air flow to or from the subsurface. The key site condition is the presence of some near-surface (or at least above the zone to be treated) stratum or barrier that causes a delay of the response of the subsurface pressures to the changes in atmospheric pressure. This pressure "lag" results in a differential pressure that can be a driving gradient to induce air flow through the "short-circuit" presented by the SVE or BV well. Atmospheric pressure

changes on the order of 25 cm of water during the passage of storms can generate significant flows, especially if the changes occur rapidly, the target zone has reasonably high air permeability, and the isolating stratum is quite tight. The daily heating of the atmosphere can also cause a pressure differential that can drive air into the subsurface during the night or extract air during the day. In order to prevent the alternating air entry and withdrawal, check valves are installed on the tops of the SVE or BV wells to limit the flow to one direction and improve effectiveness (Rossabi et al 1999). Since there is little available driving pressure, the use of passive extraction would not generally be consistent with the need for offgas treatment devices that require a pressure to deliver the offgas. The use of passive venting should be considered for remote sites or for sites that have had most of the required remediation through more aggressive treatment and a polishing phase is required before site closeout.

*d. Combined soil vapor extraction/bioventing.* As described in the previous section, the processes of volatilization and biodegradation are often hard to separate and thus SVE and BV can often be used together in a beneficial way. Whether to apply SVE, BV, or both at a site will depend on a number of factors, but the following general guidelines are suggested.

(1) At one extreme, SVE alone should be applied at sites where only volatile compounds which are difficult to biodegrade are present. BV alone should be applied at sites where only biodegradable compounds of low volatility are present or where low-to-moderate concentrations of volatile biodegradable compounds are present. A combined SVE/BV approach could be used at sites with:

- High concentrations of volatile biodegradable compounds (remove large amounts of contaminant mass and prevent air emissions with SVE, followed by polishing using BV).
- Volatile biodegradable compounds in sensitive areas where rapid response is critical.
- Both biodegradable and non-biodegradable volatile compounds.

(2) In a combined remediation system, SVE is implemented as an initial phase followed by BV as a second phase. In situ remediation of JP-4 jet fuel contamination at Hill Air Force Base in Utah used a combined approach (DePaoli et al. 1991c; Dupont, Doucette, and Hinchey 1991), as was remediation of an automobile repair facility where leaking underground storage tanks had released gasoline, waste lubrication oil, and hydraulic oil to the unsaturated zone (Zachary and Everett 1993). A combined approach would often attempt to remove the volatile contaminants first by SVE and then biodegrade the less volatile contaminants with BV. The process would change from vacuum extraction (SVE) to an air injection mode (BV) in many cases. Airflow rates would also change, possibly necessitating a smaller blower for the BV phase of operation to maximize efficiency. Paragraph 5-2a, provides further guidance pertaining to the design of combined SVE/BV systems. Note that based on USACE experience the time necessary for bioremediation of the low-volatility compounds may be long and that low clean-up goals may be difficult to achieve. However, the residual petroleum contamination generally has low mobility and low toxicity.

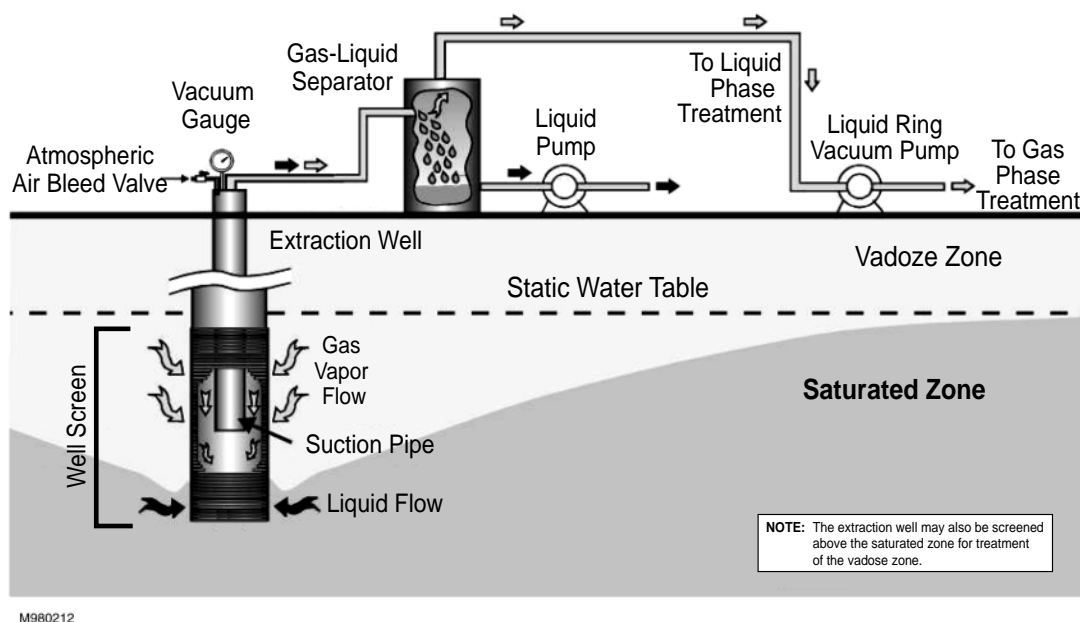
*e. Multi-Phase Extraction.* Multi-Phase Extraction (MPE) entails simultaneous extraction of vapor phase, dissolved phase and separate phase contaminants from the vadose zone, capillary fringe, and saturated zone. It is a modification of SVE that allows this technology to be extended to moderately permeable soils (intrinsic permeability  $10^{-8}$  to  $10^{-10}$  cm<sup>2</sup>). Refer to [Engineer Manual 1110-1-4010](#), Multi-Phase Extraction for a detailed discussion of this technology. In general, MPE works by applying a high vacuum (relative to SVE systems) to a well or trench that intersects the vadose zone, capillary fringe and

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saturated zone. Because the resulting subsurface pressure is less than atmospheric, groundwater rises (upwells) and, if drawn into the well, is extracted and treated aboveground before discharge or re-injection.

(1) There are a variety of implementations of MPE. The terminology presented by EPA (1997), distinguishes the variations of this technology as: "two-phase extraction" if liquids and gases are extracted within the same conduit; and "dual-phase extraction" if separate conduits for vapor and liquids are used. TPE is also sometimes referred to as "bioslurping", primarily when used for vacuum-enhanced LNAPL recovery.

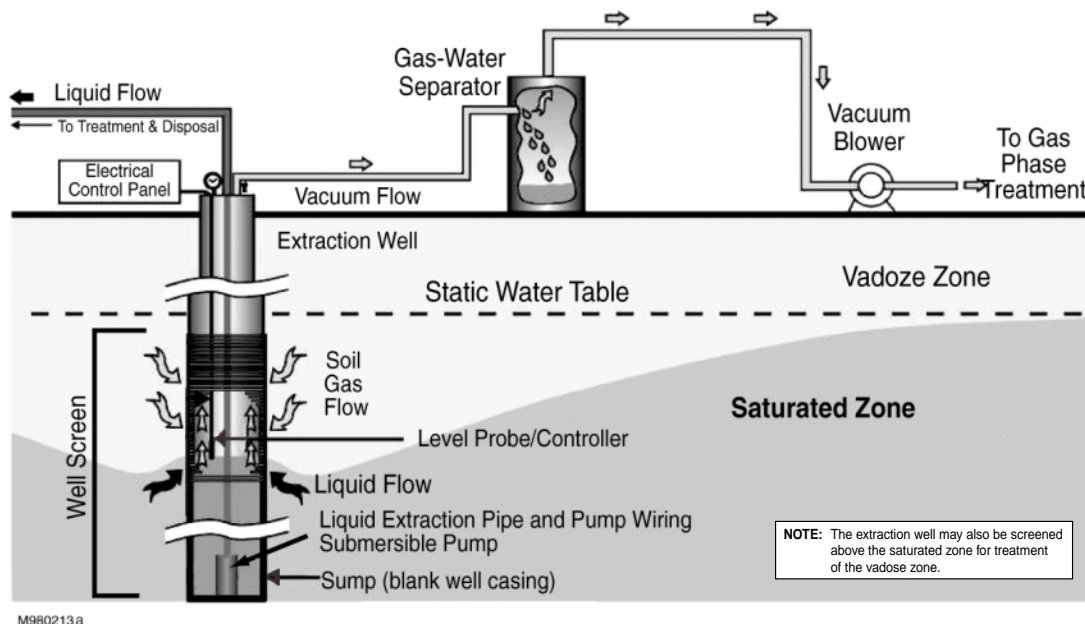
(a) Two-phase extraction (TPE). During TPE, soil gas and liquid are conveyed from the extraction well to the surface within the same conduit, which has been referred to with various names including "drop tube", "slurp tube", "stinger", "lance", or "suction pipe". A single vacuum source (vacuum pump or blower) is used to extract both liquid and gaseous phases. A common configuration is depicted in Figure 3-3. The suction pipe suspended within the well casing extracts a combination of liquids (NAPL and/or groundwater) and soil gas. These phases are conveyed to an aboveground gas-liquid separator. If extraction of NAPL is anticipated, an oil-water separator may be installed downstream of the gas-liquid separator.



**Figure 3-3. Schematic of a TPE System, showing all fluids extracted from the well via the same suction pipe. (After EPA 1997)**

(b) Dual-Phase Extraction. During DPE, soil gas and liquids are conveyed from the extraction well to the surface in separate conduits by separate pumps or blowers. A common "pipe within a pipe" configuration is depicted in Figure 3-4. It shows that a submersible pump suspended within the well casing extracts liquid, which may be NAPL and/or groundwater, and delivers it through a water extraction pipe to an aboveground treatment and disposal system. Soil gas is simultaneously extracted by applying a vacuum at the well head. The extracted gas is, in turn, conveyed to a gas-liquid separator prior to gas phase treatment. DPE is in essence a rather straightforward enhancement of SVE, with groundwater recovery being carried out within the SVE well. Other DPE configurations are also common, such as use of suction

(e.g., exerted by a double-diaphragm pump at the ground surface) to remove liquids from the well, rather than a submersible pump (Blake and Gates 1986). A line-shaft turbine pump could also be employed to remove liquids from the well, provided the water table is shallow enough.



**Figure 3-4. Dual phase extraction recovery system schematic showing separate liquids and vapor extraction conduits within the same well (After EPA 1997).**

(c) Bioslurping, is a form of TPE that aims to enhance the recovery of LNAPL, while also stimulating BV within the unsaturated zone (AFCEE 1994a; Kittel et al. 1994; AFCEE 1997). A bioslurper uses a suction tube positioned near the LNAPL-water interface to induce a pressure gradient causing water, LNAPL and gas to flow into the well. A common bioslurping configuration is depicted in Figure 3-5. As with TPE, water and/or LNAPL that is drawn into the well is lifted and conveyed to a gas-liquid separator. The liquid phase is subsequently conveyed to an oil-water separator. Bioslurping systems are designed and operated in a manner that maximizes LNAPL recovery while minimizing groundwater and gas-phase recovery. The BV aspect of bioslurping is generally less important than the primary objective of enhancing free-product recovery.

(d) The three main strategies for applying MPE are: i) vacuum-enhanced recovery of NAPL, ii) vacuum dewatering to enable SVE and/or BV to remove and/or treat organic contaminants via the gas phase, and iii) vacuum-enhanced recovery of groundwater. This last strategy is not a variation of SVE, and so is not described here.

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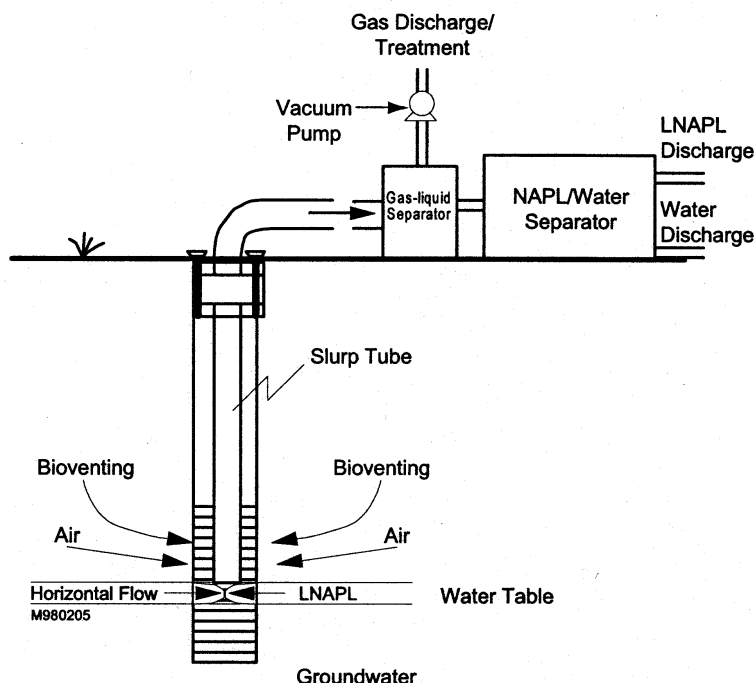
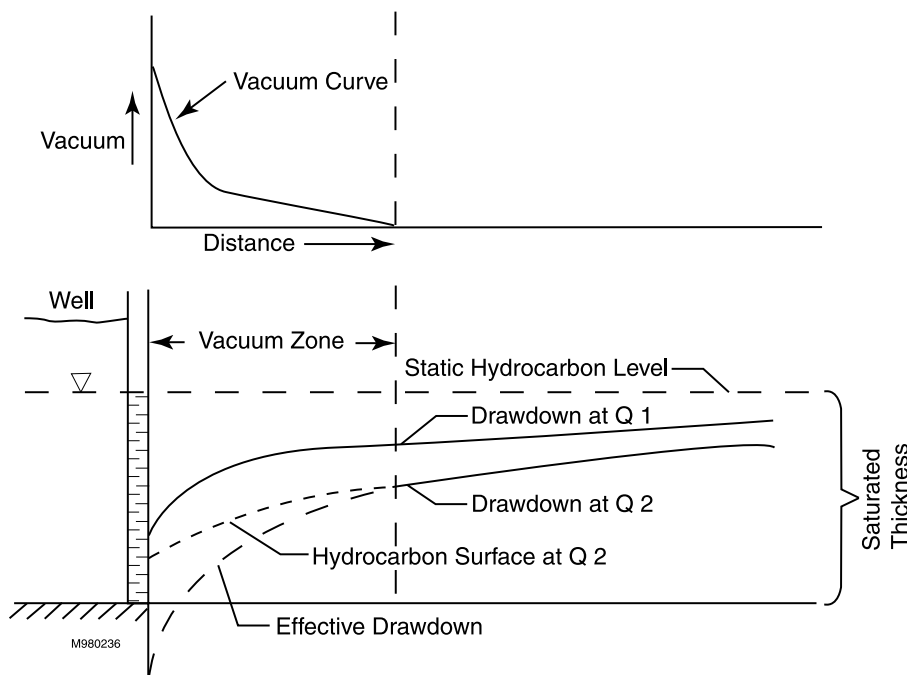


Figure 3-5. Bioslurper system (after AFCEE 1994). Not shown in this figure is the water table upwelling that occurs around the well when a vacuum is applied.

(e) Vacuum-Enhanced LNAPL Recovery. Vacuum-enhanced free-product recovery (Blake and Gates 1986; Hayes et al. 1989; API 1996) is employed, usually in medium-textured soils, to increase recovery rates of LNAPL relative to those that can be obtained using conventional means. The application of a vacuum to a recovery well increases the extraction flow rate without inducing a physical cone of depression (Blake and Gates 1986). In cases where physical drawdown is used in combination with vacuum enhancement, the effective drawdown, by superposition, is the sum of the induced vacuum (expressed in water equivalent height) and the physical drawdown, as shown in Figure 3-6. The gradient of hydraulic head that is the driving force for flow of liquid to the well is thus increased. Consequently, the volume of water extracted typically increases to an even greater extent than does the volume of LNAPL. Vacuum-enhanced recovery may also mobilize some of the LNAPL that would not otherwise be able to drain into a well because it is retained by capillary forces (Baker and Bierschenk 1995). Offsetting the increase in LNAPL removal is the necessity to treat and/or discharge a larger volume of extracted groundwater and an extracted gas stream.



**Figure 3-6. Schematic of Vacuum Effect on Perched Hydrocarbons.** Q1 is extraction rate without application of vacuum; Q2 is extraction rate with application of vacuum. (Blake and Gates 1986. Reprinted by permission of National Ground Water Association. Copyright 1986. All Rights reserved.) Not shown in this figure is the water table upwelling that occurs around the well when a vacuum is applied.

*f. Dewatering to Enable SVE/BV.* In low to moderately permeable formations that are in relatively close proximity to the capillary fringe, SVE and BV tend to have limited effectiveness. While air can flow through air-filled passages, it cannot flow through pores in such formations that tend to be saturated with water. The process of applying a vacuum to the soil to accomplish SVE also causes the water table to rise locally, or upwell, further limiting the zone through which air can flow. By removing both water and gas from the subsurface, these limitations, to some extent, can be overcome. Vacuum dewatering (Powers 1992) has had decades of use in the construction industry, where it is generally used to remove water from medium- to fine-textured soils that would otherwise flow into excavations made below the water table. When performed in VOC-contaminated soil, vacuum dewatering permits the flow of air through some of the previously saturated soil, thereby allowing VOCs residing there to partition into the air stream. In addition, soluble VOCs present in the extracted groundwater are also removed (USEPA 1997a). When carried out in soils contaminated with semi-volatile organic compounds (SVOCs) that biodegrade under aerobic conditions, vacuum dewatering enhances the aeration of previously saturated soil, thus stimulating in-situ aerobic biodegradation. It can also result in an increase in the dissolved oxygen (DO) content of soil pore water, helping to further enhance aerobic biodegradation in soil that is not able to be desaturated. It is important to underscore that compared to most other regions above the water table, the zone where air permeability is quite low (the capillary fringe) will transmit very little airflow during SVE or BV operation. Since in the case of LNAPL releases, this zone also tends to contain much residual LNAPL contamination (i.e., within the unsaturated portion of the smear zone), the problem of addressing the residual LNAPL is compounded unless the smear zone can be dewatered and exposed to airflow (Mickelson 1998). MPE offers a means to overcome this problem (Peargin et al. 1997).



g. *In situ heating.* Heat may be applied to subsurface media with the goal of increasing the rate of contaminant volatilization and subsequent removal by SVE/BV. Increased subsurface temperatures serve to increase contaminant vapor pressure and solubility while promoting biotransformation and desorption. Increased temperatures also decrease the viscosity and interfacial tension of NAPL (EPA 1997b).

(1) Techniques that have been field tested for increasing subsurface temperatures include: steam or hot air injection, radio-frequency heating (RF), electrical resistance heating, and thermal conduction heating (In situ Thermal Desorption). Other potential in situ heating techniques can also be considered based upon site-specific availability of heating sources.

(2) Steam Injection. Steam injected into a series of boreholes above and/or below the water table elevates temperatures and creates thermal gradients that expedite volatilization and subsequent vapor removal by SVE and increases both dissolved contaminant and separate-phase liquids recovery (USEPA 1998, USEPA 1997b, Udell 1996)

(a) Several demonstrations of the benefit of steam injection have been documented. Injection of steam for the remediation of the unsaturated zone at Livermore National Laboratory (Newmark and Aines 1995) has been successful.

(b) The use of steam injected at depth has been shown to create upward thermal convection which can facilitate the removal of contaminants by SVE (Adams, Smith, and Basile 1992). The most notable success of steam injection for remediation has been the Southern California Edison wood treating site in Visalia, California. The injection of steam increased mass recovery of creosote and related compounds approximately a thousand-fold relative to pump-and-treat. The injection of steam at the Visalia site dramatically increased the recovery of NAPL, mostly as a NAPL-in-water emulsion. Mass removal through volatilization and NAPL recovery accounts for much of the mass removed, but the destruction of some of the contaminants in-situ via hydrous pyrolysis oxidation (HPO) has been considered an important mechanism as well (Leif, et al. 1998)

(c) Recent work by Udell and Richardson (personal communication, 1999) has indicated that biodegradation of many hydrocarbons by thermophilic bacteria can be an important process during steam injection and particularly, as the soils cool, if air is injected as an oxygen source. Pulsing of steam into the subsurface followed by active depressurization ("huff and puff") can promote the removal of contaminants from low permeability layers, if they are not too thick, through spontaneous boiling of pore fluids following the cessation of injection and with a sudden decline of pressure in adjacent high permeability layers through application of higher vacuums. Hot air injection, alone or in conjunction with steam injection, has also been demonstrated to accelerate soil/groundwater clean-up (Stewart et al., 1998). By using hot air instead of steam, less water is injected into the subsurface and thus less contaminant dissolution and migration occurs and less water must be pumped and treated to contain it. Note that the heat content of air is much lower than the total heat content of steam (primarily due to the heat released during the phase transition from steam to water), therefore, the thermal effects of the injection of the same volume of steam will be much more significant than for the same volume of hot air.

(3) Radio-Frequency heating. RF electrical energy can also be used to heat contaminated soil. The resulting elevated temperatures can result in volatilization of the contaminants present in the soil through a combination of evaporation, steam distillation, and steam-assisted evaporation. The volatilized contaminants are then removed by an SVE system. An electrode array is installed in a series of drilled

boreholes and connected to a surface power supply. Technology descriptions claim that soil temperatures greater than 300 °C can be achieved using this method. Although temperatures significantly above 100 °C have been observed during RF heating, at the field scale temperatures above 100 °C tend to be confined to close proximity to the antenna, particularly in wet soils. It appears that the RF energy is converted to heat right at the antennae, due to what is termed a “skin effect”, and that the major transport mechanism for heat away from the antennae is thermal conduction, not radiation. Thus the antennae function as complex (expensive) thermal conduction heaters. The cost of the process is a function of soil volume, soil moisture content, and final treatment temperature, among other factors. The cost estimates reported by EPA in the CLU-IN database range from \$100 to \$250 per cubic yard, depending on the volume of soil that must be treated. When this technology is used to raise the soil temperature to around the boiling point of water, the same phenomena of in situ pyrolysis, thermal oxidation, and enhanced biodegradation may occur as in steam injection.

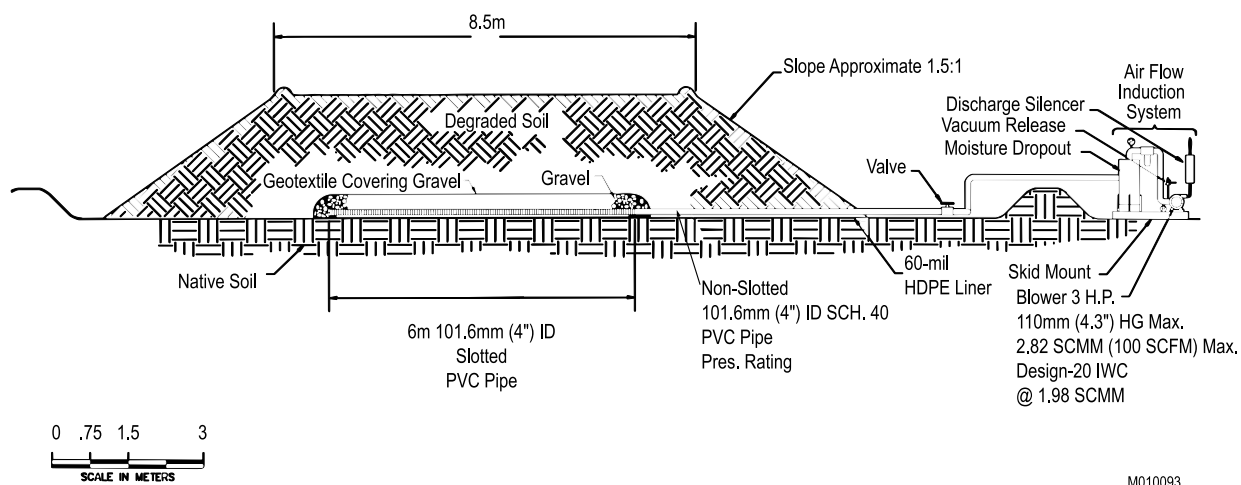
(4) Electrical resistance heating. This mechanism of soil heating relies on resistive dissipation of electrical current passed through the subsurface. As soil and groundwater are heated to water's boiling point, the water turns to steam, stripping volatile and some semi-volatile contaminants from the pore spaces. Six-phase soil heating (SPSH) is the most common application of this technique. SPSH uses voltage control transformers to convert conventional three-phase electricity into six electrical phases (Gauglitz et al. 1994a, b). These electrical phases are then delivered to the subsurface by vertical, angled or horizontal electrodes installed using standard drilling techniques. Electrodes are inserted into the ground in one or more circular arrays of six electrodes per array. Water in the soil pores conducts the electrical energy between each pair of out-of-phase electrodes. Resistance to current flow causes soil heating. A seventh neutral electrode located at the center of the array doubles as an SVE vent. Use of conventional utility transformers for SPSH results in capital costs that may be as little as one-fifth to one-tenth those for RF heating or microwave heating (Gauglitz et al. 1994b). An early SPSH field demonstration was conducted at the Savannah River Site, SC (SRS) at a location containing very low permeability clay soils contaminated with PCE and TCE. (This demonstration was part of the Volatile Organic Compounds in NonArid Soils Integrated Demonstration at SRS.) The soils were heated to 100°C and more than 99 percent of the contamination was removed, while a substantial volume of water was also removed from the soil in the form of steam (EPA 1997). SPSH also shows promise for enhancement of BV (Heath and Truex 1994). Since the soil's electrical conductivity decreases dramatically upon desiccation, this technology heats the soil to a maximum temperature of the boiling point of water. The same phenomena of in situ pyrolysis (HPO), thermal oxidation, and enhanced biodegradation can occur as described for steam injection.

(5) Electrical Conduction Heating or In Situ Thermal Desorption (ISTD). ISTD affects remediation by applying heat and vacuum to the subsurface to vaporize and destroy contaminants in situ, and/or extract the vapors and treat them above-ground. ISTD uses technology first developed in the petroleum industry for production of heavy oil, including the use of thermal wells for conductively heating the soil, and combined vacuum/heater wells for inducing flow of vapors to an aboveground treatment unit. ISTD operates at substantially higher temperatures than the other in situ heating technologies (except in situ vitrification, which melts the soil), achieving temperatures approaching 700°C. Due to the relatively long residence times during which vaporized contaminants are exposed to elevated temperatures near the heater-vacuum wells, contaminants are mostly converted to CO<sub>2</sub> and water (Vinegar et al 1998, Stegemeier and Vinegar 2000). Since ISTD operates at such high temperatures, it can be used for virtually any organic contaminant. Contaminants that have been treated by this method include PCBs, chlorinated solvents, fuel oil, coal tar compounds (PAHs), pesticides and dioxins. Removal efficiencies using ISTD are typically very high, and since this technology relies on conduction of heat through the soil, it can be applied effectively in heterogeneous and low permeability soils. The main drawback of this technology is that the heater wells

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must be installed at relatively small intervals, 5 to 10 feet, thus often requiring many wells and substantial capital investment. Recent advances in heater and heater-vacuum well design enabling installation using direct-push methods under a wide range of subsurface conditions hold promise of substantially reducing such costs.

(6) Alternative heating techniques can be considered in addition to those described. For example, waste heat from thermal oxidizer units can be used for in situ heating via injection wells. However, direct reinjection of thermally treated offgas into the subsurface may inhibit biodegradation if the injected gas is depleted of oxygen. The low heat capacity of air relative to water and soil limits the amount of heat that can be delivered to the subsurface and the subsurface temperature rise that can be achieved. Heat can also be introduced using buried heating cables or by infiltration of heated water (Sayles et al. 1992).

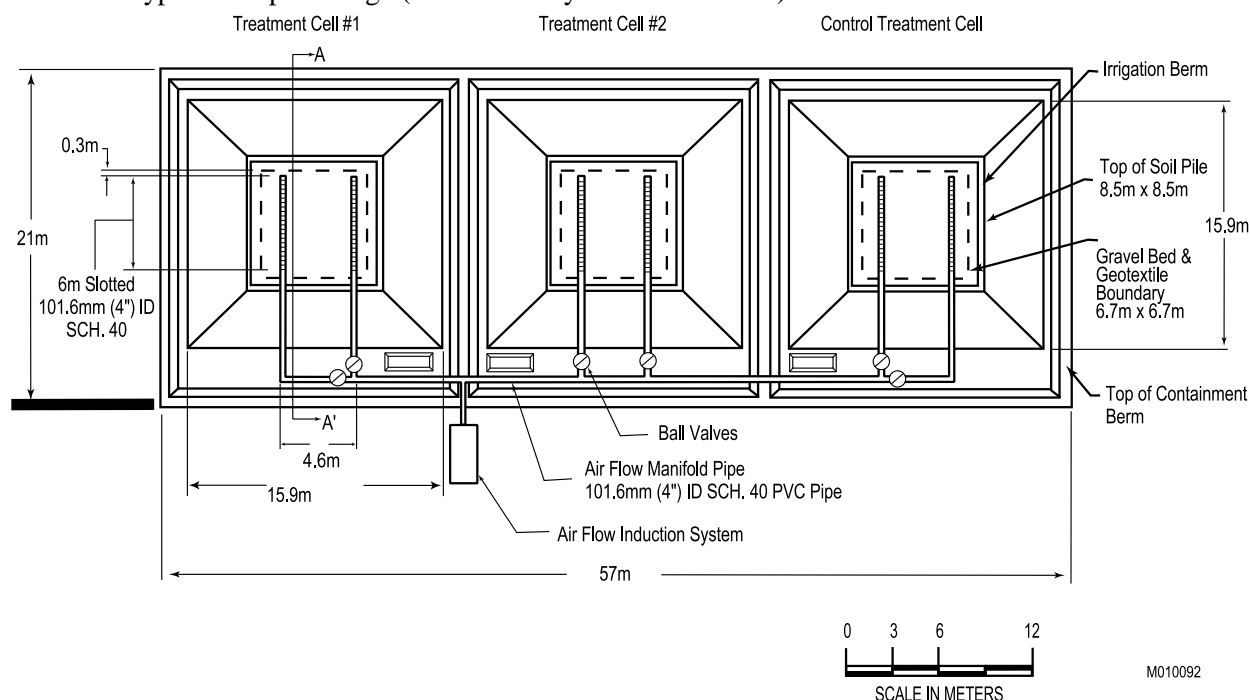


**Figure 3-7. Aboveground soil pile (cross section)**

*h. Aboveground piles.* In many instances site, operational, or regulatory constraints require that impacted soils be removed prior to treatment. Also, when USTs are removed, grossly contaminated soils will often be excavated and stockpiled before backfilling the excavation pit. In such circumstances, an alternative soil treatment method may employ an aboveground soil pile with a network of aeration pipes and mechanical blower(s).

(1) The design of an aboveground soil pile is relatively simple. A low permeability liner, typically constructed of high-density polyethylene or other synthetic material, is constructed to contain water drainage. A network of slotted pipes connected to a manifold system is placed on the liner. For an SVE application, the manifold is connected to the vacuum end of a blower to create a negative pressure in the perforated pipes. The negative air pressure at the base of the aboveground soil pile will cause air to be drawn through the soils. Extracted soil vapors can be trapped or destroyed using applicable emission control equipment. For a BV application, air can be extracted or injected, and biological activity is often further promoted in a soil pile treatment system by the addition of water, nutrients, and/or heat. Supplemental moisture can be supplied to the soil pile with a flood irrigation or sprinkler system, and a leachate collection system may need to be provided. In most cases a synthetic liner covers the entire soil pile. Air entry points are established when liners are used to ensure aeration of the pile while minimizing the entry of precipitation into the soil matrix. Piles left uncovered, or with a vegetative cover only, are at

risk of experiencing limited aeration due to saturation of the soils from rainfall infiltration. As in in situ remediation, aboveground piles may be operated in an SVE mode initially, followed by a BV phase in which air is injected. The considerations noted in paragraph 3-2c also apply here. Review of literature related to biopile construction design shows a wide variety of configurations. Space availability and logistics rather than size based performance standards often times dictate biopile dimensions. An important practical limitation on the size and geometry of the soil pile is whether the pile dimensions exceed the reach of a front-end loader. Construction complexity and the likelihood of compaction increase with larger biopiles. For this reason it is recommended that biopiles do not exceed a height of 8 feet (2.4 m). In addition, piles in excess of 10 feet in height generally require more than one level of aeration pipes. This adds further complications to the construction process. A single set of aeration pipes located at the bottom of the central portion of the biopile is sufficient for piles up to 8 feet high. Length and width dimensions are flexible and site specific but in general the shape of the pile should be long and narrow. This configuration will allow for easy construction by a front loader without compaction of the soil. An appropriate volume for a biopile is 500 cubic yards. This size is sufficiently large for the treatment of a significant volume of soil yet small enough to allow for easier aeration throughout the pile. In addition piles of this size are manageable enough so two workers are able to apply and remove the impermeable cover should nutrient addition or soil sampling be necessary. (Biopile Design and Construction Manual (TM-2189-ENV) Naval Facilities Engineering Service Center (NFESC 1996)). Figures 3-7 and 3-8 illustrate a typical soil pile design (see also Athey and Wrenn 1993).



**Figure 3-8. Aboveground soil piles (plan view)**

An advantage of an aboveground soil pile is that space requirements for soil treatment can be minimized relative to some other ex-situ treatment methods. For example, in land-farm applications where aeration is achieved by tilling, the optimum treatment zone thickness is limited to approximately 0.3 meters. In contrast, an aboveground soil pile that employs aeration pipes and blowers can increase the treatment zone thickness to about 1.2 to 3 meters. Operational costs for an aboveground soil pile system are essentially fixed for a given level of contamination and are not strongly dependent upon the size of the soil pile. Only routine inspection of the blower unit and operation of an irrigation system (if biodegradation processes are optimized) are required, and time requirements for each activity vary little in relation to treatment system

size. Other advantages include the potential for constructing a closed treatment system where all fluids can be captured and recycled. Also, excavated soils may be modified or augmented, for example, with bulking agents during transfer to the soil treatment system to mitigate factors that limit remediation. Treatment times may be shorter than those of in situ treatment processes. A primary disadvantage of this soil treatment approach is that significant labor and equipment costs are associated with excavation, soil handling, and possibly air emissions control during transfer of soil to the treatment system. Other disadvantages are that soils need to be moved again after treatment, and space requirements are greater than for in situ treatment methods.

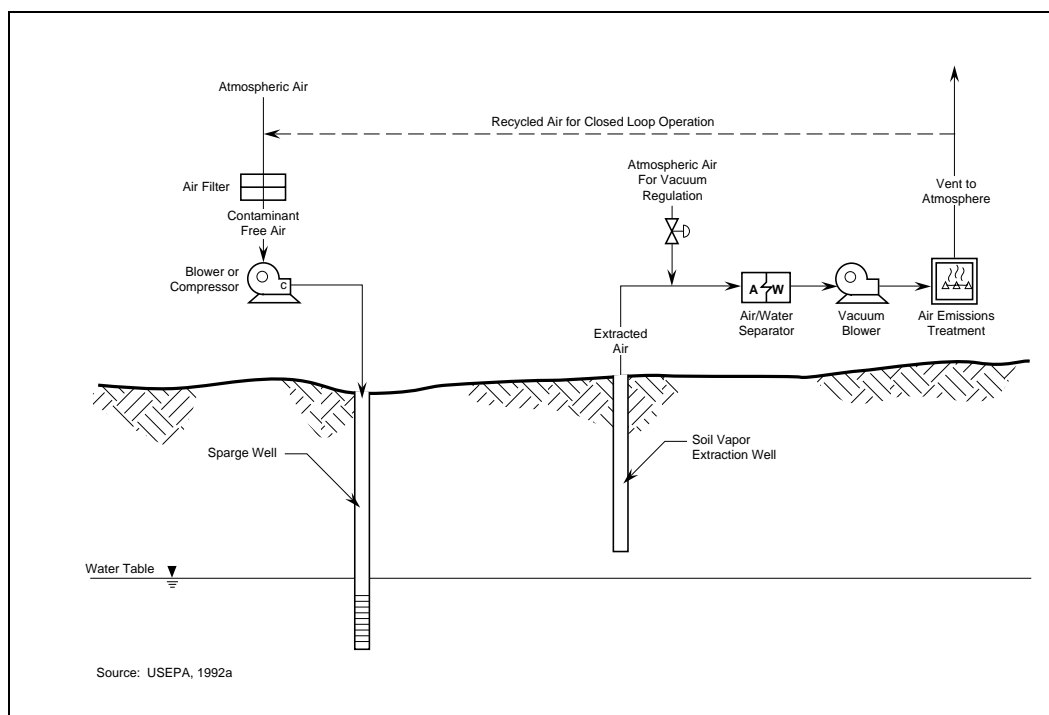
*i. Ancillary technologies.* Other remediation technologies are often applied with SVE/BV. These include air sparging, injection of gases other than air, and pneumatic and hydraulic fracturing.

(1) Air sparging. Air sparging, also referred to as “in situ air stripping” or “in situ air sparging,” is used in conjunction with SVE/BV as a means of removing contaminants from soils and groundwater in both the saturated and unsaturated zones. Upon injection below the water table, air rises toward the surface in air channels, stripping dissolved, adsorbed, and liquid VOCs. The vapor phase VOCs are transferred to the vadose zone, where they can be collected by SVE. By increasing the oxygen content in the saturated and unsaturated zones, air sparging can provide the additional benefit of enhancing aerobic biodegradation of constituents which may not have volatilized (Brown and Fraxedas 1991). Refer to [Engineer Manual 1110-1-4005, In-Situ Air Sparging](#) for a detailed discussion of this technology.

(a) Air sparging systems are often used in conjunction with SVE so that the volatile contaminants stripped from the saturated zone can be captured upon reaching the vadose zone. Due to the positive pressure gradient induced by the injection of air, the use of air sparging without SVE could potentially lead to the uncontrolled migration of contaminants into previously unaffected areas, including basements or utility conduits, creating potential explosion or health hazards.

(b) Under favorable soil and contaminant conditions, air sparging can be a timely and cost-effective method for remediating groundwater contamination (Marley 1992). A typical application of an air sparging process would take place in an unconfined, highly permeable aquifer with limited stratification exhibiting VOC contamination. Design considerations include depth to groundwater, contaminant solubility, biodegradability, vapor pressure, soil type, soil organic carbon content, degree of soil heterogeneity, presence of subsurface confining layers, and presence of NAPL.

(c) Air sparging systems commonly consist of the following components: sparge well(s), air compressor, air extraction well(s), a vacuum pump or blower, vapor pretreatment equipment, an offgas treatment system, and associated piping and instrumentation (Johnson et al. 1993). A typical air sparging configuration is presented in Figure 3-9 (USEPA 1992).



**Figure 3-9. Air sparging process schematic.**

(d) The effectiveness of air sparging depends largely on the distribution of air. In many cases, sparged air has not become well distributed within the treatment zone and flows through preferential pathways and thus bypasses significant portions of the treatment zone (Baker, Hayes and Frisbie 1995). The determination of the likely distribution of air during sparging is important to effective sparging design and to the design of the associated SVE system. Various monitoring techniques have been used successfully to determine air flow paths, including neutron probes, time-domain reflectometry, electrical resistivity tomography, and measurement of dissolved oxygen and/or tracer gases such as sulfur hexafluoride or helium in very short-screened monitoring points. Air sparging is often effective at delivering air to the smear zone or capillary fringe, under the right geologic conditions, whereas the high moisture/product content in those zones often prevents adequate remediation by SVE alone.

(2) Injection of gases other than air. Gases other than air can be injected into the subsurface to provide electron acceptors, substrates, nutrients, or tracers. Pure oxygen can be injected as an electron acceptor, but the associated explosion hazard deserves special consideration. Methane (Alvarez-Cohen et al. 1992), propane (Wackett et al. 1989), and natural gas (a mixture of methane, ethane, propane, and traces of larger alkanes) (Wilson and Wilson 1985) can be used as gaseous co-substrates for the biodegradation of trichloroethylene. Again, due to the hazard of explosion, these gases should not be injected at concentrations in air above the lower explosive limit (LEL). Nitrogen can be introduced as a gaseous phase nutrient in the form of ammonia (Dineen et al. 1990) or nitrous oxide. Phosphorus can be similarly provided in the form of triethylphosphate.

(a) In a well-documented application of air sparging and SVE, Hazen et al. (1994) injected carbon, nitrogen, and phosphorus into the subsurface in the form of methane (at concentrations of 1 to 4 percent), nitrous oxide, and triethylphosphate, respectively, at the U.S. Department of Energy (DOE) Savannah

River Site near Aiken, South Carolina. Helium was also used as a tracer gas to determine if the injected and purged gases were quantitatively recovered, and for a better understanding of flow paths, residence times, and distribution of the gases between the air injection and extraction wells. Further details on the integrated demonstration to remediate trichloroethylene contamination at the Savannah River site, including costs, are included in Schroeder et al. (1992) and LaPat et al. (1999). USACE Kansas City District has used a similar process at a formerly used Department of Defense site in Nebraska.

(b) Tracer gases should ideally be inexpensive, readily available, easily detectable with field instruments, inert, structurally similar to the gases of interest, and not normally present in the subsurface. Tracer studies are used to qualify and quantify the subsurface airflow pathways caused by soil heterogeneities and to validate air permeabilities estimated from air pressure and flux measurements. Tracer gases include sulfur hexafluoride and helium (Marley 1993). A vadose zone tracer gas study involves injecting a tracer gas into the vadose zone at various depths and distances from the vapor extraction well. The extraction well is then monitored for the arrival of the gas, yielding tracer gas travel times in the subsurface. Detailed evaluation of tracer gas test data is described in Moench (1989, 1991) and USEPA (1996).

(c) Sulfur hexafluoride ( $\text{SF}_6$ ) is often used as a tracer. Gas chromatography analysis of  $\text{SF}_6$  using an electron capture detector (ECD) can be accomplished in the field, but analysis is limited to discrete samples, and the radioactive source in the ECD requires a special license. However, inexpensive portable freon meters can be used to continuously monitor sulfur hexafluoride. These meters typically provide qualitative rather than quantitative information on the concentration of sulfur hexafluoride but are appropriate for determining travel times in the subsurface. Sulfur hexafluoride is not likely to be toxic to micro-organisms at low concentrations. Kampbell and Newell (1990) found that minor amounts, such as one percent, of sulfur hexafluoride did not, but a major amount (about 95 percent) did, inhibit biodegradation of n-butane. Helium is inert and convenient to detect using a thermal conductivity detector. Both sulfur hexafluoride and helium have molecular weights which are very different from oxygen and other air constituents; however, this is only important when gaseous diffusion is the predominant transport mechanism, not in situations involving significant advection. Methane has the advantages of low cost and ease of continuous detection using a flame ionization detector; however, methane can be produced or consumed in biological activity and is therefore not inert.

(d) Argon was injected along with air in BV field treatability tests at the Tyndall, Fallon, and Eielson U.S. Air Force Bases and at Naval Air Station Patuxent River to distinguish gaseous diffusion from oxygen consumption by aerobic micro-organisms (Hinchee, Ong, and Hoeppel 1991b). Helium is the recommended tracer gas in the U.S. Air Force protocol for field treatability tests for BV (Hinchee et al. 1992).

(3) Pneumatic/hydraulic fracturing. Soil and rock fracturing has been used for years to enhance oil recovery from low-yielding oil wells. In the context of SVE and BV systems, pneumatic/hydraulic fracturing creates fractures in soil or rock to increase bulk air permeability. The process consists of injecting air or fluids under high pressure into soil or rock until a critical pressure is reached and fractures are formed. This technique is particularly beneficial for improving advective airflow in fine-grained soils such as clays and silts. SVE airflow rates in fractured wells can increase 25 to 40 times over those in unfractured wells (USEPA 1993e). Both vertical and horizontal fractures can be created. The creation of preferential pathways using fracturing will not, however, enhance diffusion-limited transport from low permeability zones removed from direct contact with airflow pathways.

(a) The USEPA Office of Research and Development Risk Reduction Engineering Laboratory and the University of Cincinnati developed a hydraulic fracturing process (USEPA 1991e). The process creates sand-filled horizontal fractures up to 25 mm thick and radiating out from the point of injection as much as 6 meters. A viscous mixture of sand (termed a “proppant”), guar gum gel, enzyme, and water is hydraulically jetted into a borehole using a slurry pump. After injection, the enzyme additive breaks down the injected viscous fluid and leaves open fractures filled with clean permeable sand. These fractures have been placed at multiple depths at as little as 1.5 meters below the ground surface. Fracturing has been conducted in the oil industry to depths in excess of 6000 meters (20,000 feet).

(b) Another soil and rock fracturing process has been developed and patented by the Hazardous Substance Management Research Center (HSMRC) of the New Jersey Institute of Technology. The process pneumatically fractures fine-grained soil and rock by injecting high-pressure air or other gas. The process involves placing a patented air jet nozzle/packer assembly at the desired depth in the borehole and using a compressed air source to create a high-pressure pulse to fracture soil at a selected depth. To maximize the benefits of fracturing, care is taken to position the air jet nozzle/packer assembly in the borehole to ensure that only clay or silt soils are exposed between packers. Since no proppant is inserted into the fractures, they can collapse to some degree, depending on the structural strength and degree of consolidation of the soils adjoining each created fracture.

### 3-3. Pre-Design Data Requirements and Technology Screening Strategy

The primary criteria in selecting from the technology options described above are air permeability of the porous medium and volatility and biodegradability of the contaminants. Potential technologies are then further screened with a variety of site-specific factors in mind. This is illustrated in Figure 3-10. A host of other technologies should initially be screened along with technologies involving SVE and BV.

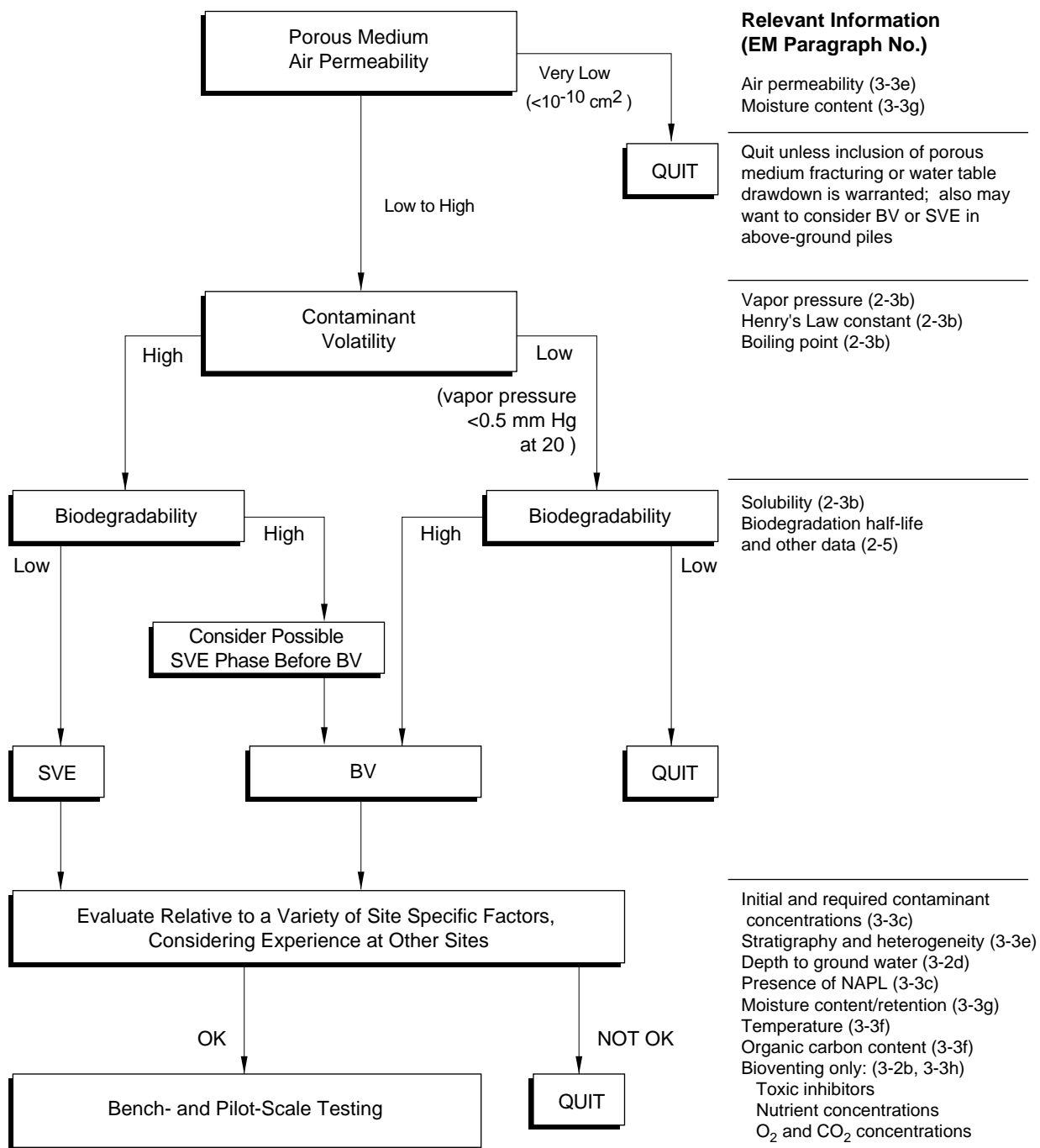
*a. Approach to technologies.* An integrated approach to SVE/BV and other technologies is preferred. For example, SVE/BV may be considered as part of a remediation system that also includes groundwater and product recovery. It is therefore critical that data be collected to address the feasibility of SVE/BV and also other technologies that might potentially be applied at the site.

*b. Site conditions and the Site Conceptual Model.*

(1) Numerous site physical, chemical, and biological conditions have a significant impact on the effectiveness of SVE/BV as a remedial alternative. These parameters are discussed in the sections below, along with site characterization data pertinent to SVE/BV feasibility and design that should be collected. Table 3-1 summarizes these site characterization data. The importance of gathering the pertinent data as early as possible cannot be overemphasized. Although one's understanding of the site will never be perfect (because characterization tools, financial resources, and sampling methods have practical limitations), one has an obligation to assemble and document lines of evidence that *converge* towards a consistent picture of the site. This picture, or conceptual model, of the site is necessarily multi-faceted and multi-disciplinary, in that it encompasses a variety of types of data. It is also dynamic, in that it evolves as additional data become available. It is important to continually reformulate the site conceptual model as new field efforts provide new information.



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Source: ENSR, 1994

Figure 3-10. Technology screening decision tree

(2) The conceptual model should describe the source(s) of the contamination, the mass released (if known), the pattern of release (i.e., was the release sudden or gradual? at one or multiple locations?), and particularly the vertical and horizontal extent of contaminant distribution in the vadose zone. There are a number of key aspects to vadose zone characterization for soil venting. In brief, these include: soil type, distribution and depth; depth to water table and its seasonal fluctuation; soil moisture content and variability; thickness of the capillary fringe; air permeability and how it varies within the domain of interest; organic carbon content and variability; type/condition of surface cover (e.g., asphalt, vegetation); presence and extent of buried structures or utilities; and topography. Any one (or a combination) of these key site elements can strongly influence soil venting effectiveness and/or present a serious limitation to soil venting. Often, site characterization data potentially important to application of SVE/BV technologies are not collected because those responsible for logging soil borings and observation pits are either not aware of them or are not prompted to recognize and systematically record them. Understanding the nature of surface horizons are critical and cannot be overemphasized. Indications of subsurface features, such as sandy or gravelly lenses in a finer-textured matrix, or macropores, that might serve as preferential airflow pathways should be logged. Soil colors and mottling can provide an indication of the zone within which the water table seasonally fluctuates. In urban or industrial locations, the contact between disturbed soil/fill and native soil should be discerned if possible. Standard methods of soil characterization should be employed for these purposes by those trained in their use (Breckenridge, Williams, and Keck 1991; USEPA 1991h).

(3) Once a conceptual model is sufficiently advanced to recognize the general nature and extent of contamination and/or source area, remediation can and often should begin. SVE/BV system designers should collect site-specific venting performance data during the design process. Such opportunities often center on SVE and BV pilot tests, but they may also entail shorter field tests such as air permeability tests, or phased SVE system installation and operation. Whatever the duration, each time the designer goes to the field to collect data on system performance much can be learned about the way the site will behave during the remediation itself. (These opportunities must be used judiciously, however, as they demand time and resources to carry out, which should be balanced against the extra expense and time that would be needed were one to end up operating a system at suboptimal effectiveness.) Each new phase of the remediation system is then predicated upon the knowledge gained from the previous phases. Design flexibility is an essential component of this approach – to accommodate design/operational changes. This can be a reason to have the designers of in situ systems also be the installers and operators, in contrast to the more common process of bid specification, contract award, system installation and operation, by firms unrelated to the designers.

(4) An initial phase of remediation or a pilot test (discussed in Section 4.0) should be employed to further the understanding of the site and the applicability of soil venting to remediate the site. The practitioner is encouraged to proceed with phased design and implementation of SVE/BV systems for a variety of reasons.

- In comparison to more traditional engineering projects (e.g., bridge design), the basis for design for subsurface environmental remediation is quite weak, typically based on a limited number of soil samples. This is not consistent with the traditional notions of 30%, 60%, 90% 100% design, common to many engineering projects that are typically predicated on solid, unchanging information.
- Often the very execution of a remediation design (e.g., installation of SVE injection and extraction wells) dramatically increases our site understanding and confidence in the site conceptual model.
- Phased implementation enables the designer to "ground-truth" design assumptions. Pilot tests typically use only a few, or sometimes only one, well/s for extraction; and test duration often

ranges from a few days to a month. Based on data from such tests, multi-well SVE systems may be designed and implemented. If the resulting system is installed in phases, full-scale operational data can be developed and then used for modifying the design of subsequent system components.

- Off-gas treatment system sizes can be minimized if an extraction system is phased in or staged sequentially, thus limiting the peak concentration and/or peak mass removal rates. Phasing (e.g., bringing a limited number of wells on-line initially) enables purchase of smaller treatment equipment (e.g., thermal oxidizer).

*c. Nature and extent of contamination.* During site characterization, the chemical properties of the site media and the nature and extent of the contamination must be determined in order to evaluate the feasibility of SVE/BV. Contaminants most amenable to SVE are VOCs that include gasoline, kerosene, many diesel fuel constituents, freons, and solvents such as PCE, trichloroethene, and methylene chloride. Table 3-2 lists contaminants for which USEPA considers SVE to be a presumptive remedy per Directive 9355.0-48FS (USEPA 1993a). Table 3-3 presents various contaminant groups and rates their amenability to SVE. The physical and chemical characteristics that make these contaminants amenable to SVE are discussed in paragraph 2-3b.

**Table 3-1. Testing and Analytical Method Summary**

Parameter	Collection Method	Analytical Method
Air-phase permeability (field-scale)	Pneumatic pump test	See Cho and DiGiulio (1992)
Air-phase permeability (core-scale)	In situ or undisturbed 50- to 75-mm diameter soil sample typical	See paragraph 4-2d and Appendix D; Corey (1986a)
Stratigraphy/heterogeneity	Soil boring and/or test pit	Visual observation; Breckenridge, Williams, and Keck (1991); USEPA (1991h)
Grain size	Split spoon or other soil sample	ASTM D422-63 (1998)
Porosity	Undisturbed 50- to 75-mm-diameter soil sample	Calculated from dry bulk density and particle density
Dry bulk density	Undisturbed 50- to 75-mm-diameter soil sample	ASTM D2850
Organic carbon content	Split spoon sample	SW-846 9060; Churcher and Dickhout (1989)
Moisture content (saturation)	Neutron logging via access tubes Tensiometers Undisturbed 50- to 75-mm diameter soil sample	Neutron gauge (Gardner 1986), ASTM D3017, ASTM D5220 Cassel and Klute (1986) ASTM D2216-92
Soil moisture retention (Capillary pressure saturation curve)	Undisturbed 50- to 75-mm diameter soil sample	Klute (1986); ASTM D2325-93
Dry end soil moisture retention	Undisturbed 50- to 75-mm diameter soil sample	Psychrometer Method (Jones, Gee, and Heller 1980)
Soil Temperature	Thermometer, Thermocouple	Portable Meter
Depth to groundwater and seasonal variations	Water table monitoring wells, Water level meter or interface gauge and surveyed well elevations	ASTM D4750
Volatile hydrocarbon content in soil gas	In situ	Downey and Hall (1994); ASTM D3416-78
O <sub>2</sub> content in soil gas	In situ	Portable meter, electrochemical cell method
CO <sub>2</sub> content in soil gas	In situ	Portable meter, infrared adsorption method
Microbial respiration rate	In situ	Hinchee et al. 1992

**Table 3-1. Testing and Analytical Method Summary**

Parameter	Collection Method	Analytical Method
Heterotrophic bacterial plate count	Split spoon or other soil sample	EPA Method 600/8-78-017
Hydrocarbon degraders	Split spoon or other soil sample	EPA Method 600/8-78-017
pH	Split spoon or other soil sample	EPA Method 9045B, 9045C
Nitrate/nitrite-nitrogen <sup>1</sup>	Split spoon or other soil sample	EPA Method 353.1-353.3; SM4500-N
Ammonia-nitrogen <sup>1</sup>	Split spoon or other soil sample	EPA Method 350.1-350.3; SM4500-NH3 A-H
Total Kjeldahl nitrogen <sup>1</sup>	Split spoon or other soil sample	EPA Method 351.1-351.4; SM4500-Norg A-C
Total and ortho phosphorus <sup>1</sup>	Split spoon or other soil sample	EPA Method 365.4; SM4500-P A-F
Barometric pressure fluctuations and subsurface response	Barometer and vacuum gauge	Portable meters, Electronic recorders can be used with electronic meters

<sup>1</sup> Listed analytical methodologies are for aqueous samples and will need to be modified for soil samples.

(1) The site investigation must also search for the presence of contaminants that are not amenable to SVE, e.g., heavy metals such as lead or cadmium, or polychlorinated biphenyls (PCBs), because remedy selection will depend on an assessment of all the contaminants of concern at the site. Table 3-3 includes examples of the more common chemicals and products that are not amenable to SVE. Their presence at a site will not necessarily preclude the selection of SVE as a partial solution or a component of a treatment train.

(2) The reader should be aware that, over the years, chemicals have often been referred to by numerous synonyms and trade names. Tetrachloroethene (PCE) is synonymous with tetrachloroethylene, perchloroethene, and perchloroethylene, for example. In evaluating historical analytical data or records of the use of chemicals or products, references such as The Merck Index (Merck & Co. 1989) can provide the synonyms of the chemicals or products that are present or were used. Consideration of possible synonyms may also be important in organizing information in electronic databases should the size of the project merit such an endeavor.

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**Table 3-2 . VOCs Considered to be Amenable to SVE**

Halogenated Volatile Organics	
Carbon Tetrachloride	
Chlorobenzene	
Chloroethane	
Chloroform	
1,1-Dichloroethane	
1,1-Dichloroethylene	
1,2-Dichlorobenzene	
1,2-Dichloroethane	
1,2-Dichloroethylene	
1,2-Dichloropropane	
1,4-Dichlorobenzene	
1,1,1-Trichloroethane	
1,1,2-Trichloroethane	
1,1,2,2-Tetrachloroethane	
Ethylene Dibromide	
Methylene Chloride	
Tetrachloroethylene	
Trichloroethylene	
Vinyl Chloride	
<b>Nonhalogenated Volatile Organics</b>	
Ketones/Furans	Acetone Methyl Ethyl Ketone Methyl Isobutyl Ketone
Aromatics	Benzene Ethyl Benzene Styrene Toluene m-Xylene o-Xylene p-Xylene

NOTE: Other compounds that have physical/chemical characteristics similar to the compounds listed may also be addressed by the presumptive remedy process.

Source: EPA 1993d

**Table 3-3. Effectiveness of SVE on General Contaminant Groups for Soil**

Contaminant Groups		Example of Contaminants	Effectiveness
<b>Organics</b>	Halogenated VOCs	Tetrachloroethene, Trichloroethene	a
	Halogenated SVOCs*	Para-dichlorobenzene	b
	Nonhalogenated VOCs	Gasoline	a
	Nonhalogenated SVOCs*	Diesel fuel	a
	PCBs	Aroclor - 1242	c
	Pesticides	Chlordane	c
	Dioxins/furans	2,3,7,8-Tetrachlorodibenzo-p-dioxin	c
	Organic cyanides		c
	Organic corrosives		c
	Explosives	2,4,6 Trinitrotoluene	c
<b>Inorganics</b>	Volatile metals	Mercury, tetraethyl lead	c
	Nonvolatile metals	Nickel, chromium	c
	Asbestos		c
	Radioactive materials		c
	Inorganic corrosives		c
	Inorganic cyanides	Sodium cyanide	c
<b>Reactive</b>	Oxidizers		c
	Reducers		b

a Demonstrated Effectiveness: Successful treatability test at some scale completed.

b Potential Effectiveness: Expert opinion that technology will work.

c No Expected Effectiveness: Expert opinion that technology will not work without enhancements.

\* Demonstrated effectiveness on some compounds in the contaminant group.

Source: modified from U.S. EPA 1991c

(3) The extent of contamination must be determined in three dimensions during the site characterization phase of the project in order to screen appropriate technologies. With regard to SVE, the unsaturated zone and the saturated zone must both be characterized.

(4) Depth of contamination affects the feasibility and design of SVE/BV systems. If contamination is limited to the ground surface, technologies other than SVE/BV will be favored. If contamination is located at depth in the saturated zone, SVE/BV alone will not be feasible. At sites where SVE/BV is feasible, the depth of contamination will influence well type (horizontal versus vertical), the well interval screened, and other design factors.

(5) The volume of contaminated soil impacts the feasibility of SVE/BV. If the volume is small, other alternatives such as excavation and offsite disposal may be more cost effective. The volume of contaminated soil also impacts many aspects of system design, such as number of wells, size of blowers, and offgas treatment system capacity.

(6) Potential offsite sources of vapor phase contaminants must be considered in determining the feasibility and design of SVE/BV systems. If significant vapor phase contamination could migrate onsite from offsite sources during SVE/BV, system design will need to include air injection wells or some other means of preventing this occurrence.

(7) The site investigator should determine whether NAPL is present. Free product in groundwater samples would be one indication of NAPL. NAPL competes with air and soil moisture for pore space within the unsaturated zone, reducing the air phase permeability. In addition, NAPL provides an ongoing source of contaminants. Unsaturated zone residual saturations of between 15 and 50 percent of available pore space have been reported (USEPA 1989c).

(8) If the presence of DNAPL is suspected, there may be concerns that implementation of SVE/BV could increase rather than reduce the risk of migration of DNAPL into deeper hydrologic units. This might be the case, for example, if DNAPL resides in fractured bedrock above the water table. It has been theorized that inducement of airflow toward an extraction well in such a setting might be accompanied by a counterflow of DNAPL deeper into the fracture system, and perhaps into the saturated zone. A Technical Impracticability waiver might be applicable in such a situation (USEPA 1993g).

(9) At the outset of the project, provisions should be made to develop an integrated approach to data management to improve the efficiency and quality of site analyses. To maximize efficiency, it is critical that appropriate data be collected at the appropriate time. An environmental database can afford greater efficiency and data quality in all aspects of project execution from initial field work to production of final reports. For example, such a system could produce preprinted chain-of-custody forms and labels for the field team and could accept standard electronic deliverable data packages from analytical laboratories. The ability to import chemical data directly from the laboratories significantly improves both efficiency and quality over manual data entry.

*d. Contaminant sampling and analysis methods.* At most sites, samples of vapor, soil, and groundwater will need to be analyzed for a variety of possible contaminants. At some sites, samples of free product (LNAPL or DNAPL) or sludges may also require testing. It is critical that all contaminants be identified and evaluated during site characterization, including compounds of little or no interest to

regulators, because their presence can affect treatment. This includes both onsite contaminants and offsite contaminants that could migrate to the site during SVE/BV.

(1) Much effort has been expended by the USACE, the USEPA, and others in developing documents specifying methods of characterizing sites with regard to contamination. These documents describe in detail the procedures and standards for developing Sampling and Analysis Plans (SAPs), Quality Assurance Project Plans (QAPPs), and Data Quality Objectives (DQOs). The documents set forth excellent general principles for performing work of known quality that satisfies project objectives. These documents are listed below.

(2) Technical Project Planning Process EM 200-1-2, USACE 1998. This manual identifies a process by which project approach is established and the data requirements (quantity, location, and quality) are set. Furthermore, the approach recommends that data collection options be developed, a sampling program be selected based on the optimum use of resources, sampling results collected and data compared to objectives.

(3) SAP: USACE 2001. Requirements for the Preparation of Sampling and Analysis Plans. EM 200-1-3. This manual provides guidance on selecting the most appropriate type of sampling approach (e.g. random or grid sampling), the numbers of samples that should be collected from each medium, and the laboratory analyses that should be performed to achieve program objectives with the desired level of confidence. Information on sampling methodology, laboratory analysis methods, and QAPPs is also provided. Table 3-4 lists the topics covered in the SAP.

(4) USEPA Region 4 1997. Environmental Investigations Standard Operating Procedures and Quality Assurance Manual. This manual describes sampling of environmental media, sample handling and preservation, decontamination of field equipment, installation of monitoring wells, and field quality assurance procedures.

(5) DQO: USEPA 2000. [link to [http://www.epa.gov/quality/qa\\_docs.html](http://www.epa.gov/quality/qa_docs.html)] Guidance for the Data Quality Objectives Process EPA QA/G-4: EPA/600/R-96/055. This document provides general guidance on the DQO development process. The first five steps of the DQO process identify what problem has started the investigation, define the decision statements that the investigation will try to resolve, determine the type of data that will need to be collected to resolve the decision statement, establish when the data will be collected, and develop a decision rule that will define how the decision will be made. The decision rule will define the parameters of interest, specify the action level and will arrive at an "If...then" statement. The sixth step of the process defines quantitative criteria expressed as limits on decision errors that the decision maker can tolerate. The final step is used to develop a data collection design based on the criteria in the first six steps. The DQO process is highly dependent on communication between the appropriate parties (samplers, chemists, engineers, modelers, project managers, QA experts, data users, and decision makers).



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**Table 3-4. SAP Format Requirements**

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**Table 3-4**  
**(Continued)**

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Source: EM 200-1-3

Note that outline for sections not as relevant to SVE and BV design have been collapsed to major headings only

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(6) DQO: USEPA 2000. [Data Quality Objectives Process for Hazardous Waste Site Investigations. Final Guidance. EPA/G-4HW.](#) This document describes the application of the DQO process to hazardous waste sites.

(7) USACE 1997. Chemical Quality Assurance for HTRW Projects. EM 200-1-6. This manual provides guidance for implementation of analytical chemistry aspects of the USACE HTRW QA program. Includes suggestions for establishment of quality control and quality assurance protocols needed to ensure fulfillment of chemical quality requirements in support of project specific data quality objectives.

(8) USACE 1998. Technical Project Planning (TPP) Process. EM 200-1-2. This manual provides guidance on utilizing the TPP process at hazardous, toxic, or radioactive waste sites. The TPP process involves identifying the project objectives, compiling all data needs for various purposes, developing data collection programs, and preparing DQO statements for compilation into a scope of work. Guidance on implementing and assessing data collection programs is also included.

(9) QAPP: USEPA 1998. Guidance for Quality Assurance Project Plans. EPA/600/R-98/018. This document provides guidance for preparing QAPPs for environmental data collection programs. The guidance addresses each of the QAPP elements as grouped by function: project management, measurement/data acquisition, assessment/oversight, and data validation and usability.

(10) QAPP: USEPA 1999. EPA Requirements for Quality Assurance Project Plans. Interim Final Guidance. EPA QA/R-5. This guidance sets requirements for QA Project Plans prepared for activities conducted by or funded by EPA.

(11)FSP: USEPA 1993. Subsurface Characterization and Monitoring Techniques, A Desk Reference Guide [EPA 625/R-93/003]. This document provides brief descriptions, advantages and disadvantages, and references for more detailed information on a extensive list of techniques of subsurface characterization including soil and soil gas.

(12)The SAP will specify the number and location of samples to be collected and analyzed. There are several different approaches to determining sample locations, including random sampling, stratified random sampling, grid sampling, hot spot sampling, judgment-based sampling, and others. These strategies are discussed in guidance documents listed below. Considerations for soil and groundwater sampling also can be applied to vapor sampling.

(13)If a random, stratified random, or grid-sampling strategy is selected, then the minimum number of samples to be collected must first be determined. The number of samples will depend on the allowable margin of error, the sample variance, the relative sample variance, the desired confidence level of the result, and the precision of the sampling and laboratory methods. These parameters vary depending upon the phase of the project, the area under study, and the parameters being tested. For example, during a field soil gas survey, the margin of error, desired confidence level, and precision of measurements may all be less rigorous than when the site is being evaluated for compliance with cleanup standards. A tool to assist in this approach is the Visual Sampling Plan software developed by Battelle Pacific Northwest National Lab.

(14)Extensive research has been done on the various techniques of collecting water and soil samples and the effects those techniques may have on sample integrity, especially with regard to VOCs and metals. The method best suited for a given site is dependent on expected analytes and concentrations, the number of locations to be sampled, and trade-off considerations of cost versus convenience. For example, if groundwater samples will be collected frequently from the same well, dedicated pumps or bailers may be appropriate. However, the collection of soil samples for VOCs must be performed as described in SW-846 Method 5035 (USEPA 1986). Samples should be collected for low-level (acid solution preservation) and/or high-level (methanol preservation) analyses depending on the data quality objectives (e.g., required detection limits). Guidance on the collection of samples by this methodology can be found in the Interim Chemical Data Quality Management (CDQM) for USACE Hazardous, Toxic and Radioactive Waste (HTRW) Projects (USACE, 1998) and Chapter 3 of the Multi-Phase Extraction Manual (EM 1110-1-4010).

(15)Soil contaminant concentrations are often remarkably heterogeneous. In some situations, it is appropriate to composite soil samples so that more aliquots of soil can be represented in fewer analytical tests, thus reducing analytical costs. Compositing is inappropriate for light solvents and VOCs because compounds volatilize and are lost from the sample during mixing, but compositing may be acceptable for nonvolatile compound analyses. For C12 to C17 diesel, compositing may result in the loss of 10 to 20 percent of the diesel mass.

(16)Air (vapor) samples are collected and analyzed in a number of different ways. Guidance on air sampling and analysis techniques is provided in the following documents:

- National Institute for Occupational Safety and Health (NIOSH) 1984. *Manual of Analytical Methods*. Third Edition. February 1984.
- 40 Code of Federal Regulations, Part 60, Method 18, 1997.

- USEPA 1999. *Compendium of Methods for the Determination of Toxic Organic Compounds in Ambient Air*. EPA/625/R-96/010b
- USEPA 1988b. *Field Screening Methods Catalog*. EPA/540/2-88/005.
- Hewitt, A.D., *Establishing a Relationship Between Passive Soil Vapor and Grab Sample Techniques for Determining Volatile Organic Compounds*, US Army Corps of Engineers, September 1996.
- American Society for Testing and Materials (ASTM) 1993. *Standard Guide for Soil Gas Monitoring in the Vadose Zone*. ASTM D 5314-93.

(17)Some commonly used techniques for analysis of VOCs in air samples are:

- Direct injection into a gas chromatograph (GC) equipped with a flame ionization, photoionization, electron capture, or other appropriate detector.
- Adsorption onto Tenax, charcoal, Ambersorb, and/or other appropriate sorbent material(s), followed by GC or GC/mass spectrometry (GC/MS) analysis.
- Cryogenic trapping followed by GC analysis.
- Collection in specially treated canisters followed by GC/MS analysis.

(18)By their very nature, contaminants that are amenable to SVE are amenable to being measured during soil gas surveys. Frequently, field soil gas measurement is a useful way to characterize the nature and extent of soil contamination at a site. Often field measurements of soil gas contaminant concentrations confirmed by a limited number of laboratory analyses are sufficient for site characterization. However, a good quantitative correlation between soil gas and soil concentrations can seldom be obtained. This is particularly true when higher concentrations of contaminants are present due to residual NAPL. When contrasting soil gas and soil sample concentrations it is helpful to keep in mind that soil sample results represent contaminants in all soil compartments (NAPL, dissolved, sorbed, and vapor phases), while soil gas measures only those in vapor. USEPA 1988b and USEPA 1991g above provide guidance on soil gas survey methodology. Soil gas surveys can also provide an indication of contaminant concentrations that can initially be expected in SVE offgas. Long-term offgas contaminant concentrations, however, are not well predicted by soil gas surveys.

(19)Soil gas surveys are instrumental in determining BV feasibility (Downey and Hall 1994). High vapor phase contaminant and carbon dioxide concentrations coupled with low oxygen concentrations may indicate that biodegradation is occurring but is oxygen-limited. These conditions would support further consideration of BV as a remedial alternative. Soil gas surveys can also locate areas with heaviest contamination in which venting wells might be situated.

(20) Soil gas surveys can be more economical than traditional drilling and soil sampling techniques. However, soil gas monitoring is often impossible in very moist soils, particularly in fine-grained units. Interference from leaked ambient air may lead to erroneous results in such situations. Soil gas surveys of deep units may also be difficult due to soil heterogeneities such as clay layers. Gaseous diffusion in the subsurface, particularly along high permeability conduits such as utility lines, can lead to high soil gas concentrations in areas at some distance from the true source area. Furthermore, the nature of the surface covering and recent precipitation events can affect observed soil gas concentrations. Tight surface coverings can result in high concentrations over wide areas surrounding a release due to limited escape of contaminant vapors to the atmosphere and recent precipitation events can displace contaminant vapors downward and draw in clean atmospheric air into the subsurface.

*e. Air permeability.* Air permeability, the ability of soil to permit the passage of air, is one of the most critical parameters affecting SVE/BV feasibility and design. It is a function of solid matrix properties and moisture content. A number of investigators (Brooks and Corey 1964; Van Genuchten 1980; Mualem 1986) have developed equations to estimate this value from pressure-saturation, bulk density, and saturated hydraulic conductivity data (paragraph 2-3c).

(1) Air permeability has a profound influence on airflow rates and contaminant recovery rates. Coarse-grained soils typically exhibit large values of air permeability and more uniform airflow patterns. Both of these factors tend to promote increased contaminant recovery rates. By contrast, fine-grained soils are characterized by small values of air permeability and airflow patterns that are primarily restricted to macropores or secondary permeability zones such as fractures. This results in increased removal of contaminants from these zones; however, at distances away from these high permeability zones, where residual contaminants may be bound in a fine-grained matrix, recovery rates are reduced (Johnson et al. 1994). In these cases, air permeability should be measured in the field to more realistically assess the influence of macro-features (secondary flow features). Air permeability of fractured rock is highly variable based on the degree and interconnections existing between fractures. If the fractured rock is also porous or if the contaminant has been present in the fractures over a long period, significant contaminant mass may reside in the rock matrix. In this case, diffusion may be a dominant process in removing mass from the rock matrix. Air permeability can be measured or estimated by a variety of methods, several of which are presented in paragraphs 4-2a and 4-5 and in Appendix D. Soils with air permeabilities less than about  $10^{-10}$  cm<sup>2</sup> may not be amenable to SVE/BV (USEPA 1993d).

(2) As mentioned before, moisture is a primary determinant of air permeability, and is held at higher saturation levels in fine-grained soils than coarse-grained soils. Plastic fine-grained soils, moreover, if dried to the point of overconsolidation and cracking to form secondary flow features, have been observed on a macro-scale to exhibit air permeabilities comparable to fine- to medium-grained sands. The designer needs to assess the appropriateness of soil sample derived properties (such as permeability) in cases where macro-features may dominate.

(3) Heterogeneities play a significant role in the distribution of contaminants within the unsaturated zone and are caused by spatial variations in soil type, layering, porosity, and moisture content. During the operation of an SVE/BV system, these variations may influence airflow patterns and ultimately contaminant recovery rates within the unsaturated zone. For example, if the unsaturated zone is comprised of alternating layers of coarse- and fine-grained soils, airflow may be restricted to the coarse-grained strata. Contaminants are often removed from the finer grained strata at much slower rates. Soil borings, cone penetrometry, and soil profile examinations of the exposed faces of test pits are among the methods to obtain information on physical heterogeneities.

(4) In some instances, underground utilities such as storm and sanitary sewers or the backfill material associated with these features may produce short-circuiting of airflow associated with an SVE/BV system. As a result, airflow may be concentrated along these features rather than within the zone requiring treatment. In addition, these features may also provide migration pathways for both free-phase liquids and vapors within the unsaturated zone. As a result, the orientation and geometry of these features may dictate the direction in which the liquids or vapors migrate. Often, accurate as-built drawings of underground utilities do not exist, so persons familiar with the site should also be consulted. Basements of nearby buildings and other features that may affect flow should be noted.

(5) Topography and the nature of the ground surface will affect SVE/BV. An impermeable surface will tend to enhance horizontal airflow and increase the radius of influence. A permeable surface will do the opposite and will increase the amount of atmospheric air entering the subsurface. Surface constraints such as buildings, roadways, and utility systems may make SVE/BV an attractive remedial alternative relative to other options. If pavement is present at the ground surface, its integrity should be examined. Any cracks should be noted and, if possible, sealed (see paragraph 5-16).

*f. Solid matrix properties.* Data on solid matrix properties (introduced in paragraph 2-3c) should be collected during site characterization. Grain size analyses provide information on the distribution of particle sizes in a soil. Typical porosities for sands and gravels are 25 to 40 percent. Porosities for fine-grained soils are higher, typically 35 to 50 percent for silts and 40 to 70 percent for clays (Freeze and Cherry 1979). Porosity can be calculated from measurements of bulk density using Equation 2-4.

(1) The subsurface temperature significantly influences the vapor pressure of a given compound. As the temperature increases, the vapor pressure increases. Jury et al. (1987) reported that for intermediate weight organic compounds, the vapor pressure may increase as much as four times for each 10°C increase in temperature.

(2) The fraction of organic carbon in a soil (foc) affects the ability of a given compound to partition to the gaseous or aqueous phases. Soils characterized by high foc values have a tendency to limit the amount of mass that partitions from a soil particle to the surrounding pore space. In contrast, soils characterized by low foc values tend to promote such partitioning.

*g. Water.* The moisture content of a soil influences the magnitude of the air permeability. Water competes with air and NAPL to occupy pore space within the soil and ultimately reduces the ability of vapors to migrate through the unsaturated zone due to a reduction in air pathways.

(1) In addition, moisture content has a significant impact on gas phase partitioning. Farmer et al. (1980) and Aurelius and Brown (1987) have demonstrated that volatilization decreases as the soil approaches full water saturation. By contrast, based on work nearer the dry end of the moisture spectrum, Lighty et al. (1988) and Houston, Kremer, and Marwig (1989) reported that adsorption of VOCs to soil increases as the water content decreases. This was attributed to the fact that when some moisture is present, water molecules compete for the same adsorption sites as the contaminants. As a result, water molecules displace the contaminants from the soil surface for subsequent transport by SVE. In summary, while low water saturations favor higher relative air permeabilities, desiccated conditions retard desorption of VOCs and should be avoided (USEPA 1991d). Desiccation can be prevented by passing the injection air through a humidification unit. Moisture content in soil samples can be measured gravimetrically. Moisture



content can also be monitored in situ by a variety of methods, including tensiometry, neutron thermalization, and time domain reflectometry (Baker and Wiseman 1992).

(2) The unsaturated hydraulic conductivity and the air permeability of a soil are functions of its moisture content. As a result, under various levels of soil vacuum (i.e., pressures less than atmospheric), the moisture content, as well as the unsaturated hydraulic conductivity and air permeability will change (Hillel 1980a). Capillary pressure-saturation (i.e., soil moisture retention) measurements enable one to quantify the ability of a soil to retain moisture under a specific vacuum condition and consequently to predict the effects of pressure and saturation on air permeability (Baker and Wiseman 1992). The tests may be considered as a measure of the storage capacity (i.e., the air-filled porosity) of a soil at a specific equilibrium vacuum. They indicate whether the soil exhibits a distinct air-entry suction and its value. They also provide an indirect measure of the pore size distribution, which more directly affects SVE than does the grain size distribution. Methods of measuring capillary pressure-saturation are given in Table 3-1.

(3) Moisture content is also important for bioventing applications. Since most if not all of the degradation occurs in the water phase, if the moisture content drops below a threshold, biodegradation will diminish significantly. For bioventing, moisture content should be between 5% and 20% (Downey 1995). In application of passive bioventing to soils at Kirtland AFB, New Mexico, Johnson and others found that moisture was the limiting factor for bioventing and supplemental moisture and nutrients were added in the vapor-phase (Johnson et al 1999). If moisture content is too high, water will occlude pore spaces and prevent movement of air (i.e., oxygen) into the soils. Insufficient oxygen levels will, in turn, reduce the rates of biodegradation.

(4) Humidity is important in SVE and BV. Water vapor, like liquid water, enhances desorption of contaminants from soil particles. Davies (1989) states that the critical moisture regime for SVE applications is in the range of 94 to 98.5 percent relative humidity in the soil gas. Below this range, VOCs are more tightly bound to soil and may not volatilize as readily.

(5) The water table surface acts as a no-flow boundary for airflow and is used to define the thickness of the vadose zone. Subsequently, the depth to groundwater as well as seasonal variations need to be evaluated, in part to ensure that the SVE/BV system will not be flooded during a high water table period.

*h. Microbiology.* Concentrations of electron acceptors, such as oxygen, and respiration byproducts, such as carbon dioxide and methane, can provide an indication of whether biodegradation is naturally occurring in the subsurface. Where oxygen is depleted, forced air may be used as an oxygen source to promote aerobic microbial biodegradation within the unsaturated zone. One advantage of introducing oxygen as a gas phase is that gases possess greater diffusivities than liquids (Hinchee et al. 1992). As a result, gas phase oxygen can be delivered much more rapidly (i.e., at rates several orders of magnitude greater) than oxygen delivered in the liquid phase. Secondly, the oxygen concentration in the gas phase (approximately 21 percent in air) is much greater than the oxygen concentration that can be delivered in the aqueous phase (about 0.0008 percent in aerated water).

(1) In contaminated soil, a variety of heterotrophic and specific hydrocarbon degrading bacteria are often present. These bacterial populations may be limited by electron acceptors (e.g., oxygen), electron donors (e.g., organic matter) and nutrients (principally nitrogen and phosphorus). In the case of fuel-contaminated soil, the populations are usually limited by the availability of the electron acceptor (i.e., oxygen). If BV is a possible candidate remediation technology for a site, and conditions exist (e.g.,

extremes of pH, elevated heavy metals concentrations) that raise doubts as to the viability of the indigenous microbial community, it is advisable to screen soil samples for microbial activity. High bacterial populations in soil can be indicative of conditions that should accommodate bioremediation. Low populations do not necessarily mean that bioremediation is not feasible but may indicate that toxicants, or other factors, are suppressing microbial activity. If the number of aerobic bacteria increase after bioventing is initiated, or increase compared to a control area not being biovented, it can indicate that conditions supporting microbial activity have improved through bioventing. The heterotrophic plate count, formerly known as the standard plate count, is a procedure for estimating the number of live aerobic heterotrophic bacteria in water and wastewater. The method can also be adapted for soil samples. Plates (petri dishes) containing a medium of food and nutrients (usually nutrient rich agar) are inoculated with the soil or groundwater sample. The plates are incubated for about one week, during which time colonies arise from pairs, chains, clusters, or single cells, all of which are counted and included in the term “colony-forming units (CFU).” The results are typically expressed in exponential numbers, such as  $2 \times 10^6$  CFU/g-soil. Several bacterial enumeration methods (including pour plate, spread plate, most probable number (MPN) tubes and the membrane filter method) and different media are described in APHA/AWWA/WEF (1992) and Soil Analysis, Part 2, Chemical and Microbiological Properties, 2<sup>nd</sup> Edition (Page et al, 1982). The numerical results from different enumeration methods may not be directly comparable. Therefore the same method should be used to evaluate different areas of the site of conditions over time. The spread plate method is often used for bioremediation monitoring and is routinely performed by commercial laboratories. These methods can also be adapted to counting specific contaminant degraders in contaminated zones by using a medium that contains one or more of the organic contaminants from the site as the sole carbon source. Observing these numbers increase or being greater in the treatment area than in background, non-contaminated areas, could also be interpreted as evidence of stimulated bioremediation. While bacteria counts alone provide only an indirect, and rather imprecise measure of the useful biological activity at a site, when coupled with corroborating data such as measurements of respiration rate and moisture and nutrient levels, they may aid in the interpretation of trends in BV performance. Published and measured bacteria count values are site specific and can vary greatly, and thus care should be used in comparing data between sites. Increased bacterial numbers could also be due to stimulation of the biodegradation of naturally occurring organic matter and not the contaminants of concern.

(2) Other methods of estimating the number of soil bacteria include phospholipid fatty acid analysis, enzyme activity analysis, and ATP bioluminescence assays. The assessment of microbial activity under actual field conditions can also be elucidated during the site assessment process through the measurement of soil gas oxygen and carbon dioxide concentrations during soil gas survey activities. Depressed oxygen and elevated carbon dioxide levels throughout the site relative to background levels provide evidence of field microbial viability.

(3) Soil samples should be tested for pH to determine whether conditions are too acidic or alkaline to support abundant microbial populations. pH also provides a basis for assessing the likelihood that CO<sub>2</sub> will be generated as a result of aerobic degradation, and whether this gas should be monitored. Optimal pH is generally in the range of about 6 to 8. Soil samples should also be examined for concentrations of macronutrients, specifically nitrogen (N) and phosphorus (P). Deficiencies in available N and/or P may limit microbial populations and activity. In such cases, amending the soil with nutrients may lead to increased biodegradation rates. Analyses for nitrate/nitrite-N and ammonia-N provide a measure of the N which is readily available to microorganisms, while total Kjeldahl N (TKN) measures the total pool of organic N plus ammonia in the soil, comprising both readily available and less available N (such as that in biomass proteins). Similarly, ortho P indicates the concentration of readily available P, while total P includes less available forms of P.

3 Jun 02

(a) A review of over 60 U.S. Air Force pilot- and full-scale BV projects concluded that natural nutrient levels have been sufficient to sustain some level of biological respiration at all sites when oxygen is provided (Miller et al. 1993). TKN at the sites ranged from <50 to >700 mg/kg. Lower TKN concentrations were more common; about one-third of the sites had TKN concentrations less than 50 mg/kg. Total P concentrations also ranged from <50 to >700 mg/kg. Sites were more evenly distributed throughout this range. It was noted that a C:N:P ratio of 250:10:1 is optimal, though not necessarily required.

(b) Another review of Air Force BV experience concluded that natural nutrient levels as low as 20 mg/kg TKN and 3 mg/kg total phosphorus have been sufficient to sustain biological respiration when oxygen is provided (AFCEE 1994).

*i. Regulatory constraints and objectives.* The regulatory context under which SVE/BV is performed may depend on the input and approval of several government agencies. While primacy for regulatory oversight usually rests with the state in which the site is located, the USEPA will also be involved if the site is on the National Priorities List (NPL) or if excavation of constituents listed under the Resource Conservation and Recovery Act (RCRA) is required. In addition, sites near surface water bodies may also be under Coast Guard jurisdiction. Sites in or near wetlands may also be subject to local wetland regulation. Care must be taken to ensure that all of the relevant agencies involved are satisfied with the remedial approach and design.

(1) Regulatory cleanup standards are central to SVE/BV feasibility and system design. Cleanup requirements may be too stringent for SVE/BV to be feasible. If SVE/BV is feasible, cleanup standards will impact the duration of remediation, offgas treatment requirements, and other variables.

(2) Sometimes, the only permit required for an SVE/BV system installation and operation is a well permit. However, the SVE system will produce an air stream which may require treatment prior to discharge to the atmosphere, thus in many states an air discharge permit will be required. State air treatment requirements vary widely and may be site-specific; therefore, contact the state directly or through the customer to determine permit requirements.

(3) In many cases, including the regulatory agency representatives in the project planning process (refer to EM 200-1-2) for site characterization, pilot testing, etc. will expedite the implementation of the regulatory approval project and provide information that answers questions important to those agencies without additional mobilization to the field.

*j. Customer's objectives.* The SVE/BV screening process is driven largely by technical and regulatory issues. However, the customer's objectives and preferences should also be incorporated into the remediation plan.

(1) An area where the customer will have concern is in project cost. One method of cost control is extension of the project schedule to spread out capital costs over a longer time period, with annual costs comprising a larger portion of overall project costs. This tactic of amortizing capital costs over a longer time period is especially appealing to customers who operate on strict annual budgets. The customer can also influence project cost and schedule by requiring that field work take place in times of moderate climate, as extreme weather conditions generally increase the cost and time required for field activities. Future land use anticipated by the customer is another consideration. A customer may prefer to exceed

minimum cleanup requirements to enable a site to be used for a particular purpose once remediation is complete.

(2) Other customer concerns may include site access and minimizing disruption of ongoing site operations. Finally, in the interest of community relations, the customer may wish to incorporate aesthetic considerations (such as landscape improvement and noise mitigation) into the remediation design.

*k. Cost as a component of technology screening.* A comparison of the costs of SVE/BV and other technologies can be used to eliminate options which are not economical. At NPL sites, the required level of accuracy of technology screening cost estimation is precisely defined during the Feasibility Study process. At other sites, the level of accuracy may be defined more by customer needs than regulatory requirements. It is essential that the level of accuracy and the comprehensiveness of the technology screening cost estimate be similar for each technology so that the comparison is valid. In addition, a net present value analysis should be performed to allow comparison of alternatives with different design lives and cash flow schedules. The technology screening cost estimate is similar to the feasibility estimate described in Chapter 10. Refer to Chapter 10 and ER 1110-3-1301 for guidance on cost estimating.

### **3-4. Examples of Screening-Level Evaluations of SVE/BV**

Screening level evaluations take place at the technology review stage. Several examples of screening-level evaluations of SVE and BV are described below.

*a.* A site in Puerto Rico was contaminated with a variety of solvents from leaking tanks, primarily methylene chloride, acetone, methyl isobutyl ketone, and xylenes. Methylene chloride DNAPL was present in one confined area. Soil contamination extended to 4.5 to 6.0 meters below the ground surface. Site soils were heterogeneous sand and silt fill in the contaminated area, surrounded by clay. The water table was about 3 meters below the ground surface, and zones of perched groundwater were also present between 1 and 3 meters. SVE and BV alone were ruled out primarily because of high groundwater elevations. Another problem with SVE was that some of the volatile contaminants (e.g., acetone and ketone) were highly soluble and therefore tend to partition more to the aqueous than the vapor phase. The selected remedy was SVE/BV in conjunction with groundwater extraction, steam injection, and biostimulation by nutrient addition.

*b.* A wood-treating NPL site in the southeastern United States was contaminated with high concentrations of polynuclear aromatic compounds, arsenic, and lead. Soils were heterogeneous sands and silts, and the water table was 1.0 to 1.5 meters below the ground surface. SVE was ruled out because the contaminants were not very volatile. BV was ruled out primarily because of high groundwater elevations.

*c.* As mentioned in paragraph 2-3c, laboratory studies of soil samples yielding capillary pressure-saturation curves (also known as moisture retention curves) can provide useful screening level information on the feasibility of SVE/BV. These laboratory evaluations are particularly useful for borderline sites having medium- to fine-grained moist soils. Qualified geotechnical laboratories can test soil samples for pressure-saturation data, and some can model the data points to provide a pressure-saturation curve which indicates the air entry suction. The curves are typically constructed by fitting a Brooks and Corey (1966) or Van Genuchten (1980) function to the data (see paragraph 2-3c). The air entry suction can then be compared with pressures that can economically be applied at a site to screen the site for the feasibility of SVE/BV.

*d.* Capillary pressure-saturation studies in the laboratory and SVE pilot studies in the field have been conducted in parallel at three sites, including a site with an area of sand and an area of finer-grained soils (Baker and Wiseman 1992) and in a saprolite (Baker and Bierschenk 1995). In all cases, agreement of the laboratory and field data was good. These data suggest that if a careful pressure-saturation laboratory study indicates that SVE/BV is infeasible at a site, a pilot study will likely yield the same conclusion. If the laboratory data indicate SVE/BV is feasible, a pilot study in the field should then be conducted to examine possible preferential flow pathways. This screening approach can allow the feasibility of SVE/BV to be determined in a cost-effective manner for sites with finer-grained moist soils. The importance of understanding the relationship between pressure-saturation relationships and the feasibility of SVE is illustrated by the following example: SVE was selected as the remedy at a Superfund site in New England. The soils were largely silty clays. Although laboratory air-permeability testing suggested adequate permeability to achieve some mass removal, field testing did not achieve significant air flow at many locations. Further work demonstrated that moisture content was high and the water was held by large capillary forces that SVE could not overcome.

*e.* Between 1992 and 1995, the U.S. Air Force applied BV technology at over 125 sites at 50 Air Force installations, located in all 10 USEPA Regions and in 28 states (Miller et al. 1993; AFCEE 1994a). These sites were selected from the universe of Air Force sites using the following screening criteria:

- Petroleum hydrocarbons were to be the primary contaminants, although the additional presence of detectable chlorinated solvents was acceptable.
- Soils were to be permeable to air - sandy soils were preferable, but less permeable soils were also acceptable because the Air Force desired to study a wide range of soil types in the BV initiative.
- The water table was to be at least 1.5 meters below grade, so that dewatering would be unnecessary.
- No significant amount of free product was to be present, although a sheen was acceptable.

Approximately 70 percent of the sites contain greater than 25 percent silt and clay fractions. Out of 117 test locations selected with the above criteria and tested by January 1994, BV was infeasible at only 3 locations, due to a combination of high water tables, high moisture content, and fine-grained soils (Miller et al. 1993; AFCEE 1994a).

*f.* The U.S. EPA and the U.S. Coast Guard (USCG) carried out an 18 month-long joint demonstration of in situ remediation of a JP-4 jet fuel spill at the USCG Support Center, Elizabeth City, North Carolina (Cho et al., 1997). The remediation approach for this site was combined SVE/BV following de-saturation of "smear zone". To document actual removal of hydrocarbons, core samples were collected and analyzed for total petroleum hydrocarbons (TPH) in August 1992 prior to air injection and SVE, and in September 1994 following the demonstration. From the difference in soil concentrations measured between the two core sampling events, approximately 2,000 kg of the TPH, 55% of the original mass, was removed. The initial goal of reducing the TPH concentration in soil to < 100 mg/kg was not attained. Monitoring of SVE off-gas revealed that about 1,700 kg of hydrocarbon vapor was collected through the SVE system, accounting for 85% of the actual removal, and leaving only 300 kg hydrocarbon attributable to enhanced

biodegradation. However, biodegradation rates estimated from the rates of O<sub>2</sub> uptake measured during four in situ respiration tests (ISR - described in Chapter 4) conducted between 7 and 18 months after startup ranged from 0.72 to 13.9 mg hydrocarbon/kg soil/day (mg/kg/d), with an overall average of ~3 mg/kg/d. Assuming that 3 mg/kg/d was representative of the entire 18 month-long demonstration period, the total estimated removal by biodegradation over the period is >1,600 kg, nearly equal to the mass collected by SVE. Cho and coworkers (1997) concluded that the demonstration did not achieve mass balance. The estimates of mass removed by SVE combined with BV was greater than the amount actually documented by analyses of cores. Since the amount removed by SVE was based on direct measurement of offgas, while the amount removed by BV was estimated from indirect measurements of O<sub>2</sub> uptake, they concluded that the BV estimates were invalid. They offered possible explanations of inaccurate O<sub>2</sub> uptake measurements due to channeling, or overestimation of biodegradation due to oxygen consumption during chemical oxidation of reduced sulfur and iron minerals that may have formed from anaerobic microbial activity. Even so, they suggested that biodegradation would play an increased role compared to physical removal by SVE as the mass of volatile components diminished.